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SINGLE STAGE EXPERIMENTAL EVALUATION OF VARIABLE GEOMETRY GUIDE VANES AND STATORS

PART II - ANNULAR CASCADE INVESTIGATIONS OF CANDIDATE VARIABLE GEOMETRY DESIGNS

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ABSTRACT

Tests were conducted in an annular cascade tunnel to (1) evaluate the feasibility of using a slot near the leading edge of a stator to aid flow turning at high positive incidence angles, and to (2) provide comparative performance data for two candidate variable geometry inlet guide vane designs.

The stators were tested at an incidence angle of 14.1 degrees. A slot located at 22.5% chord improved the suction surface diffusion. The best slot configuration tested reduced the wake loss coefficient from 0.224 without a slot to 0.177.

A variable geometry guide vane with articulated flaps had the lowest loss coefficient (0.021) in the zero-prewhirl position.

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SECTION I
SUMMARY

Tests were conducted in an annular cascade tunnel to (1) evaluate the feasibility of using a slot near the leading edge of a stator to aid flow turning at high positive incidence angles, and (2) provide comparative performance data for two candidate variable geometry inlet guide vane designs. These preliminary tests were conducted as part of the design effort under the overall program. The test stators were 65-series airfoil sections having a chord length of 6.5 inches and a constant equivalent camber of 38.8 degrees. A baseline test was conducted with an unslotted stator, followed by tests of three different stator slot geometries. The stator configurations were tested at an incidence angle of 14.1 degrees. A slot located at 22.5% chord improved the suction surface diffusion as evidenced by the measured pressure coefficient distributions. Testing of one of these slot configurations resulted in a decrease in loss coefficient from 0.22 to 0.18 and an increase in lift coefficient from 0.795 to 0.945 when compared to an unslotted stator.

The test guide vanes were basically 63-series airfoil sections having a chord length of 5.46 inches and a camber angle of 72.8 degrees. They were designed to provide 30 degrees rotor prewhirl at simulated cruise conditions and zero prewhirl at simulated sea level takeoff conditions. The two candidate variable geometry designs were compared on the basis of profile loss in the zero-prewhirl position. The design that incorporated two articulated flaps to provide a smooth variation of camber angle over a wide range of prewhirl angles resulted in a loss coefficient value of 0.021. The design that incorporated separate flap sections, forming a venetian blind configuration at zero-prewhirl conditions, had a loss coefficient of 0.069. Reference loss data and air turning angle were also obtained for the fully cambered position of the guide vanes, which was the same for both of the variable geometry designs. The loss coefficient was 0.017 and the turning angle was 26.7 degrees.

SECTION II
INTRODUCTION

Pratt & Whitney Aircraft is engaged in a program under NASA Contract NAS3-7604 to investigate variable geometry inlet guide vanes and stators designed to provide flow vector diagram adjustment for stable compressor operation at sea level takeoff and high Mach number cruise operating conditions. One variable geometry guide vane configuration, and two variable geometry stator configurations will be designed, fabricated, and tested as part of a typical front stage in a 0.5 hub/tip ratio single-stage compressor research rig.

As part of the overall design effort for the program, variable geometry features for guide vanes and stators were analyzed for general mechanical feasibility and aerodynamic performance. Candidate designs that resulted from this preliminary screening were evaluated for final selection by means of a limited number of tests in an annular cascade tunnel.

The variable geometry stator evaluation involved a series of tests to select the geometry of a slot to aid flow turning around the forward section of a stator at the relatively high incidence angles encountered during cruise operation. The stator vanes were first tested without slots to determine the chordwise locations of suction surface minimum pressure and boundary layer separation. The stator vanes were subsequently slotted approximately halfway between these locations. This slot location was consistent with the preferred slot location relative to minimum pressure and separation points as determined under another program (Reference 1*).

Two candidate variable geometry designs for inlet guide vanes were tested to determine which concept had the lowest profile loss in the design (axial flow) position. Reference loss data were also obtained for the fully cambered position of the guide vanes, which was the same for both of the variable geometry concepts.

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*References are found in Appendix D.

These annular cascade tests were limited in extent and, consequently, only mean radius data were obtained for, essentially, one flow condition, angle of attack, and Mach number for each type of blade row. This report presents details of the test equipment, procedures, and test results for this annular cascade study.

SECTION III
TEST EQUIPMENT

A. TEST FACILITY

The annular cascade tests were conducted in the compressor research facility shown in figure III-1.* A J75 engine was used in conjunction with a two-stage ejector system to draw air through the compressor rig. Flow rates up to approximately 110 lb/sec were possible at atmospheric inlet pressure. Ambient air entered the compressor test rig through a 78-foot inlet duct, plenum chamber, and bellmouth inlet, and exhausted through the ejector system. Airflow rate was measured using an ASME standard thin plate orifice located in the inlet duct. The inlet throttle valve was set in the fully open position for all tests. The plenum was sufficiently large to provide, essentially, stagnation conditions upstream of the bellmouth inlet to the test rig, and a 7-degree diffuser ahead of the plenum assured uniform flow conditions across the inlet. The inlet duct and plenum were mounted on a track, and could be rolled away from the compressor rig inlet to facilitate configuration changes. The plenum was sealed to the compressor rig inlet section by means of an inflatable rubber tube seal.

B. ANNULAR CASCADE RIG

The annular cascade rig is shown schematically in figures III-2 and III-3 for the stator and guide vane tests, respectively. Inner and outer wall diameters at axial stations of interest are tabulated in the figures. The desired gas path was formed by wooden filler sections. A split test case provided convenient accessibility for blading changes without removing the entire rig from the test stand. Both the prewhirl vane and stator blade row assemblies were divided into two 180-degree sections.

The test section for stator evaluation comprised a row of 50 prewhirl vanes, which set the stator inlet conditions, and a row of 20 stators, which turned the flow back to the near-axial direction. The prewhirl vanes were fabricated from stainless steel and tack-welded to the shrouds. The stator and stator shrouds were fabricated from aluminum, and the stators

*Figures are presented in Appendix C.

were positioned at a nominal blade chord angle of 15.4 degrees with dowel pins and held in place with machine screws. (See figure III-4.) For the slotted stator tests, only the stator vanes in one of the 180-degree sections were slotted.

For the variable geometry guide vane evaluation, the test section was modified to permit the installation of 14 oversize inlet guide vanes. The support struts and prewhirl vanes used for the stator evaluation were removed, and the test guide vane assembly, shown in figure III-5, was installed as shown in figure III-3. All of the guide vane configurations were fabricated from aluminum. The vane sections were positioned in the shrouds with dowel pins and held in place with machine screws.

Fully cambered blades were used in both halves of the shroud assembly for the full cambered test. The two guide vane geometries for design (axial flow) conditions were evaluated simultaneously by installing seven vanes of one design in the upper half of the shroud assembly, and seven vanes of the other design in the lower half of the assembly (figure III-5).

One of the sets of test stator vanes was installed, as shown in figure III-3, to maintain concentricity of the flow path for the guide vane tests.

C. BLADING DESIGN

1. Stator

The stator configuration for slot evaluation (figure III-6) was intended to investigate the effectiveness of a forward slot in reducing the leading edge separation. A conventional 65-series airfoil (65-1.6-09) section designed with a loading level representative of the upper limit of current design practice was selected for this purpose. A 6.55-inch stator chord was used to permit installation of static pressure instrumentation and to facilitate dimensional control of slot geometry. The stator vanes had a constant equivalent circular arc camber of 38.85 degrees from hub to tip, and were untwisted. Calculated mean-radius values of D-factor loading, inlet Mach number, and incidence were 0.61, 0.50, and 15.6 degrees, respectively.

The prewhirl vanes that were used to set the stator inlet conditions were designed for turning angles of 51.6 degrees at the hub to 49.3 degrees at the tip. NASA 63-series airfoil sections were selected to provide the relatively high turning angles.

Details of the stator and prewhirl vane designs are given in table III-1.

2. Variable Geometry Guide Vane

The two candidate variable geometry guide vane concepts, shown in figure III-6, were designed to provide approximately 30-degree rotor prewhirl at the simulated high Mach number cruise conditions, and zero rotor prewhirl at design (simulated sea level takeoff) conditions. The 63-series airfoil section was selected to accomplish the relatively high turning for cruise conditions. The guide vanes were designed with a constant camber of 72.8 degrees (defined by tangents to the mean camber line at 0.5 and 95% chord) and a chord length of 5.48 inches to ensure a sufficiently large wake for accurate quantitative evaluation. Design data for this series airfoil was obtained from Reference 2. Vane row solidity (0.744 at the hub to 0.599 at the tip) was commensurate with the rotating cascade program guide vane design. Other details of the guide vane design are presented in table III-1.

Table III-1. Summary of Design Data for Prewhirl Vane, Test Stator, and Test Guide Vane

	PREWHIRL VANE			STATOR			GUIDE VANE		
	HUB	MEAN	TIP	HUB	MEAN	TIP	HUB	MEAN	TIP
Series Airfoil	63	63	63	65	65	65	63	63	63
Chord (in.)	3.00	3.00	3.00	6.55	6.55	6.55	5.46	5.46	5.46
Thickness Ratio	0.06	0.06	0.06	0.09	0.09	0.09	0.09	0.09	0.09
Camber (deg)	72.8	72.8	72.8	38.8	38.8	38.8	72.8	72.8	72.8
Inlet Metal Angle (deg)	-18.2	-18.2	-18.2	34.8	34.8	34.8	-31.9	-31.9	-31.9
Exit Metal Angle (deg)	54.6	54.6	54.6	-4.0	-4.0	-4.0	40.9	40.9	40.9
Aspect Ratio	1.306	1.306	1.306	0.554	0.554	0.554	0.92	0.92	0.92
Blade Chord Angle (deg)	35.7	35.7	35.7	15.4	15.4	15.4	22.0	22.0	22.0
Solidity	1.412	1.294	1.200	1.234	1.137	1.054	0.744	0.660	0.599
Inlet Absolute Mach Number	0.271	0.271	0.271	0.528	0.499	0.477	0.214	0.214	0.214
Inlet Absolute Air Angle (deg)	0.0	0.0	0.0	51.6	50.4	49.3	0.0	0.0	0.0
Exit Absolute Air Angle (deg)	51.6	50.4	49.3	8.6	7.6	7.3	30.0	30.0	30.0
Diffusion Factor	--	--	--	0.622	0.607	0.589	--	--	--
Loss Coefficient	0.139	0.139	0.139	0.190	0.210	0.228	0.139	0.139	0.139
Deviation (deg)	3.0	4.2	5.3	12.6	11.6	11.8	10.9	10.9	10.9

D. INSTRUMENTATION

Instrumentation for the stator and inlet guide vane test programs was provided primarily for the measurement of mean radius wake profiles, chordwise pressure distribution, and inlet and exit air angles. The axial locations of instrumentation stations are shown in figure III-2 for the stator evaluation tests, and in figure III-3 for the guide vane evaluation tests. The two instrumentation stations of primary concern for the stator tests were 2 and 3A. Station 2 was located just ahead of the test stators,and station 3A was about 1/2 chord length downstream of the stators. An instrumentation layout of the test section for the stator program is shown in figure III-7. For the guide vane program, the inlet of the test section was the plenum chamber and the exit was station 0. An instrumentation layout for the guide vane test section is shown in figure III-8.

Weight flow for both test programs was measured by means of an ASME standard thin plate orifice located in the inlet duct.

Plenum pressure and temperatures were measured by means of six wall pressure taps and six total temperature probes.

1. Stator Program Instrumentation

Stator inlet conditions were measured at stations 1 and 2. Section views of the flow path at stations 1 and 2 showing the circumferential location of the instrumentation are presented in figure III-9. At station 2, inlet air angle measurements were obtained at three circumferential locations with 20-degree wedge traverse probes. Three Kiel probes measured midspan total pressure. Three static pressure taps were located on the outer wall and three on the inner wall of station 2. A 20-degree wedge traverse probe was also located at midspan-midchannel, approximately 1/2 chord length downstream of the inlet guide vane row (station 1).

Stator exit conditions were measured at station 3A (figure III-9). A section view of the flow path at this station is shown in figure III-9. Four 20-degree wedge traverse probes were used for stator exit air angle measurement, and four Kiel probes were used for midspan total pressure measurement. Two 16-tube rakes were used for midspan stator wake total pressure measurements. Eight static pressure taps were located around the outer wall to detect the presence of flow nonuniformity that might occur as a result of having unslotted stators in the lower half of the test section. Two static taps were located on the inner wall.

Three test stators, designated A, B, and C, located in the test section, as shown in figure III-7, were instrumented with static pressure taps to provide chordwise pressure measurement. The chordal locations of the taps for the unslotted and three slotted vane configurations (designated configurations 1 through 4, respectively) are given in table III-2. All taps were located at 50% span. The location of taps in the slot region for configurations 2, 3, and 4 is shown in figure III-10.

Table III-2. Slotted Stator Vane Pressure Tap Locations, Percent of Chord

	PRESSURE SURFACE	SUCTION SURFACE			
CONFIGURATION	1-4	1	2	3	4
Tap No.	Vane B	Vane C	Vane C	Vane A	Vane C
1	4.74*	7.49	7.49	7.03	7.03
2	10.24**	12.07	12.09	12.09	12.09
3	16.80***		17.26	17.26	17.26
4	21.85****	17.26	18.34	22.30	18.56
5	25.03	25.05	20.04	25.21	20.04
6	30.06	30.06	25.05	30.06	25.05
7	35.07	35.07	30.06	35.07	30.06
8	40.08	40.08	35.07	40.08	35.07
9	45.10	45.10	40.08	45.25	40.08
10	50.11	50.02	45.10	50.11	45.25
11	55.12	55.12	50.02	55.12	55.12
12	60.13	60.13	55.12	60.13	60.13
13	65.14	65.14	60.13	65.14	65.14
14	70.15	70.15	65.14	70.15	70.15
15	75.16	75.16	70.15	75.16	75.16
16	80.17	80.17	75.16	80.17	80.17
17	85.18	85.18	80.19	85.18	85.18
18	90.19	90.30	85.18	90.19	90.19
19	95.20	95.20	95.20	95.20	95.20
		Vane A	Vane A	Vane C	Vane A
20		3.40	3.36	5.96	3.36
21		9.03	9.01	11.61	9.20
22		11.90	11.92	16.65	12.08
23		20.01	20.01	18.84	19.32
24		22.58	20.01	24.75	20.39
25		27.56	22.58	27.56	22.58
26		32.57	27.56	32.57	27.56
27		37.88	32.57	37.88	32.57
28		42.59	37.88	42.59	37.88
29		47.60	42.59	47.60	42.59
30		52.70	47.60	52.61	52.61
31		57.62	57.62	57.62	57.62
32		62.63	62.63	62.63	62.63
33		67.64	67.64	67.64	67.64
34		72.65	72.65	72.65	72.65
35		77.66	77.66	77.66	77.66
36		82.67	82.67	82.67	82.67
37		87.68	87.68	87.68	87.68
38		92.70	92.70	92.70	92.70

For Configuration 3: * = 4.28
** = 9.40
*** = 11.92
**** = 22.61

2. Guide Vane Program Instrumentation

A section view of the flow path at the guide vane exit station (station 0) showing the circumferential location of the instrumentation for the design (axial flow) and cruise guide vane configurations is given in figure III-11. For the axial flow test, air angle measurements were obtained at four circumferential locations with 20-degree wedge traverse probes. Four Kiel probes were used for midspan total pressure measurement. Two wake probes were used to measure total pressure distribution behind the venetian blind guide vane configuration. One wake probe was utilized behind the variable camber guide vane configuration. The wake probes were set perpendicular to the rig centerline.

For the cruise guide vane geometry test, air angle was measured at two circumferential locations with 20-degree wedge probes. Midspan total pressure measurements were obtained with two Kiel probes. Two wake probes were used to measure the guide vane exit total pressure profile. The wake probes were set at an angle perpendicular to the expected air exit air angle.

Three static pressure taps were located on both the inner and outer walls for each configuration.

3. Description of Probes

Details of the 20-degree wedge, Kiel, and wake probes are shown in figure III-12. The wedge probe contained side pressure pickups for airflow angle measurement and total pressure and temperature sensors.

The stator wake probes contained 16 total pressure tubes, and the guide vane wake probes contained 20 total pressure tubes. The pressure tubes were 0.042-inch (OD) hypo tubing spaced as shown in figure III-12.

4. Instrumentation Readout

All pressure and air angle data were automatically recorded. Traverse probe data (total pressure and air angle) were recorded on magnetic tape at the rate of 60 samples (2.5 inches probe travel) per minute. Steady-state pressure measurements were obtained using a Scannivalve multichannel pressure transducer system that provided automatic data recording on IBM cards. Temperatures were read on a precision potentiometer, and manually recorded on IBM cards.

Plenum conditions and flow measuring orifice measurements were also recorded on manometer tubes in the test stand control room to permit setting the desired operating conditions.

SECTION IV
PROCEDURES

A. TEST PROCEDURE

1. Stator Program

A test was conducted initially with unslotted stators to obtain suction surface pressure distribution to aid in selecting slot location and to obtain performance data for comparison with the slotted stator performance data. To minimize fabrication for the slotted tests, only the stator vanes in the upper half of the annulus were slotted. The circumferential distribution of wall static pressure obtained with slotted stators in the upper half of the annulus and unslotted stators in the lower half was not appreciably different from the pressure distribution obtained initially with unslotted stators. Therefore, it was considered adequate to slot only half of the test vanes for this preliminary slot configuration investigation. A comparison of wall static pressures at the stator exit with and without slotted stators in the upper half of the test section is shown in figure IV-1. A tabulation of the wall static pressure values is presented in table IV-1 in Appendix B.

The stator tests were conducted at an approximate stator inlet Mach number of 0.50 and a corresponding corrected weight flow of 70.5 lb/sec. Flow conditions were set by controlling the J75 slave engine exhaust flow through the ejector system. When steady-state flow conditions were established, fixed instrumentation data were recorded, using the Scannivalve system. The traverse probes were then actuated, followed by a second recording of fixed instrumentation.

2. Guide Vane Program

The inlet guide vane program consisted of two tests. The first test was conducted with simulated cruise geometry guide vanes to determine if the vane could achieve the desired air turning with a reasonably low profile loss. The second test was conducted to compare the total pressure losses of the variable camber and venetian blind vanes for the axial flow condition. The venetian blind vanes were installed in the top half of the vane shroud and the variable geometry vanes were installed in the bottom half.

The guide vane inlet Mach numbers were approximately 0.22 and 0.30, respectively, for the cruise geometry and axial flow geometry tests. The procedure for guide vane tests was the same as that for stator tests.

B. DATA REDUCTION PROCEDURE

1. Preliminary Data Reduction

An IBM computer program was used to convert magnetic-tape-recorded data and data recorded on IBM cards to engineering units. Traverse data (total pressure, total temperature, and air angle), obtained at approximately 0.04-inch increments across the span, were automatically plotted (as well as tabulated). The tabulated data were used to select midspan values of total pressure and air angle. The plotted data were inspected for general profile shape, as well as for inlet guide vane wake and secondary flow influences.

2. Parameter Calculation

The following parameters were calculated for the analysis of test data and the evaluation of slotted stator and variable geometry guide vane performance. These parameters were calculated from midspan data. Symbols are defined in Appendix A.

a. Static Pressure Coefficient

Stator vane surface static pressure measurements are presented in the form of pressure coefficients, defined as follows:

$$C_p = (p_\ell - \overline{p}_2)/\overline{q}_2$$

where:

p_ℓ = local vane surface pressure

$\overline{p}_2$ = arithmetical average of wall static pressures upstream of stator (station 2)

$\overline{q}_2 = \frac{\gamma}{2}\,\overline{p}_2 M_2^2$

$\gamma = 1.40$

$M_2 = f\left(\overline{p}_2/\overline{P}_2\right)$

and

$\overline{P}_2$ = area-average total pressure at station 2 (midspan)

b. Total Pressure Loss Coefficient

Total pressure loss coefficient is defined as

$$\bar{\omega} = \frac{\bar{P}_u - \bar{P}_d}{\bar{q}_u}$$

where:

$\bar{P}_u$ = area-average total pressure upstream of vane row (midspan)

$\bar{P}_d$ = area-average total pressure downstream of vane row (midspan)

$\bar{q}_u = \frac{\gamma}{2} \bar{p}_2 M_2^2$ for stator vane rows

$\bar{p}_2$ = arithmetical average of inner and outer wall static pressure at station 2.

For the guide vanes, inlet dynamic pressure (q_u) was obtained as a function of inlet Mach number, which was determined from isentropic flow relationships using measured weight flow, plenum pressure, temperature, and the appropriate flow area. Area averaging was considered sufficiently accurate for comparison purposes.

d. Stator Diffusion Factor

Stator diffusion factor is defined as:

$$D = 1 - \frac{V_{3A}}{V_2} + \frac{\Delta V_{\theta\ 2-3A}}{2\sigma V_2}$$

where:

V_2 = velocity at inlet to stator (station 2)

V_{3A} = velocity at exit of stator (station 3A)

$\Delta V_{\theta\ 2-3A}$ = change in tangential velocity across the stator.

e. Stator Lift Coefficient

Lift coefficient is defined as:

$$C_L = \frac{\int \left(p_p - p_s\right) dc}{\overline{q}_2 c}$$

where:

p_p = static pressure on pressure surface

p_s = static pressure on suction surface

c = stator chord length

$\overline{q}_2$ = dynamic pressure at station 2 as defined in the preceding paragraph.

The pressure times area term, $(p_p - p_s)dc$, was obtained by manual integration of the static pressure distributions. Each section of the slotted stators was treated as a separate airfoil for the integration.

f. Air Turning

Because of the influence of vane wakes and secondary flows, the air angle measurements at midspan for different probes at a particular station varied by several degrees. Evaluation of the effect of slots on turning angle was therefore based on a study of individual probes selected on the basis of their proximity to wakes and the uniformity of indicated pressure and angle profiles in the midspan region.

SECTION V
RESULTS AND DISCUSSION

The objectives of this preliminary annular cascade program were to establish the feasibility of a leading edge stator slot to aid the flow turning over the leading edge at a relatively high incidence angle and to obtain qualitative comparison of two candidate variable geometry inlet guide vane designs. A limited number of slot configurations were evaluated to provide slot geometry guidelines. Consistent with these objectives, methods to improve the quality of the flow, and, thereby, the data, were not considered.

A. STATOR EVALUATION

1. Unslotted Blade Performance

a. Prewhirl Vane

Midspan air angle measurements at the stator inlet are summarized in table V-1 in Appendix B. The average of the air angles indicated for the single probe at station 1 is 49.2 degrees, compared with a design air angle of 50.4 degrees. The differences in air angle measurements obtained with the three probes at station 2 are attributed to the proximity of these probes to prewhirl vane wakes and the stator leading edges. An angle of 49.2 degrees results in a stator incidence of about 14.4 degrees compared to the design value of 15.6 degrees. This average angle is in good agreement with the average prewhirl vane exit air angle obtained for this prewhirl vane under the previous test program (Reference 1). The prewhirl vane wake total pressure loss was also documented under a previous test program (Reference 1). Because the prewhirl vane inlet Mach number for the present program and the previous program were approximately the same, established prewhirl vane loss was used to obtain stator inlet total pressure for the present analysis.

b. Stator

The pressure coefficient (C_p) distribution for unslotted stator configuration 1 is presented in figure V-1. Table V-2 in Appendix B lists the pressure coefficients for this configuration. It can be seen in figure V-1 that the pressure coefficient curve begins to flatten out at approximately 50% chord on the suction surface, which indicates apparent flow separation at this chordal location. This result was corroborated by flow patterns obtained by means of injecting dye through static pressure taps on the suction surface.

The midspan wake total pressure profile for the unslotted stator configuration is shown in figure V-2 in Appendix B. Total pressure data are presented in table V-3 in Appendix B. The loss coefficient for this configuration was 0.224, which reflects the observed suction surface boundary layer separation.

The D-factor loading for the unslotted stator was 0.48, compared with a design value of 0.607. This difference is attributed to the fact that stator incidence was 1.5 degrees less than predicted, and that end-wall boundary layer buildup in the relatively long stator chord length caused a relatively higher midspan exit velocity than predicted. Midspan exit air angles for the unslotted stator configuration are listed in table V-4. The air angle measurements at the circumferential locations of 228.5 and 328.8 degrees showed considerable disagreement with each other and with the consistent angle measurements obtained at circumferential locations of 24.4 and 65.8 degrees. The probe readings at circumferential locations of 228.5 and 328.8 degrees were therefore not used to obtain an average exit air angle. The average midspan exit air angle obtained with the remaining two probes is 8.7. This average angle combined with the average stator inlet angle of 49.2 degrees results in a stator turning angle of 40.5 degrees, which is less than the predicted turning angle by only 2.3 degrees.

Table V-4. Midspan Stator Exit Air Angles at Station 3A

Circumferential Location (deg)	24.4	65.8	228.5*	328.8*	Average
Configuration 1 (unslotted)	8.7	8.6	3.2	14.0	8.7
Configuration 2	7.2	9.0	1.6	8.6	8.1
Configuration 3	7.2	8.0	3.4	11.5	7.6
Configuration 4	9.4	6.8	-4.5	8.9	8.1

*Not Used in Average Value

2. Slot Configuration Selection

a. Slot Location

The following general criteria were used to determine the location of slots for the stator vanes:

1. The slot should be located upstream of the point of flow separation, because the slot flow could not effectively turn the primary flow back toward the suction surface if it were exhausted into a separated region
2. The slot should be located in a region where the pressure difference between the suction and pressure surfaces is sufficiently high to provide adequate slot flow.

As mentioned previously, flow separation on the unslotted vane occurred at approximately 50% chord. The slot was, therefore, located at 22.5% chord on the suction surface, which was as far forward as mechanically possible. This placed the slot exit in the steep portion of the pressure gradient, approximately halfway between the minimum pressure point and the point of separation.

b. Slot Geometry

Definitions of the geometry nomenclature and a summary of the slot dimensions for the three slotted stator configurations are presented in figure V-3. Slot geometry variables of primary concern were slot contraction ratio, Y_2/Y_1, Coanda radius, R_I, and radius, R_p.

The slot exit width, Y_2, was calculated on the basis of an arbitrary slot flow requirement equal to approximately 3% of the primary flow, using the theoretical pressure drop between the pressure and suction surfaces. The three slot configurations that were evaluated are shown in figure V-4. These configurations were based on the results of unslotted blade testing and the results of the slot geometry investigation reported in Reference 1.

3. Slotted Stator Performance

Midspan total pressure wake profiles for the three slotted stator configurations are shown in figure V-5. Midspan total pressure data for all of the stator configurations are summarized in table V-3 in Appendix B. Total pressure data for the wedge and Kiel probes were translated to a single stator channel and are superimposed on the wake profiles. The unslotted stator wake profile, included for comparison with the slotted stator wake profiles, indicates that there was no appreciable shift of the wake toward the suction surface when a slot was added. All of the slotted stators have shallower wakes than the unslotted stator, but the wakes for configurations 2 and 4 are wider than the wake for the unslotted stator. Configuration 3 has a noticeably narrower wake profile than that of the unslotted stator. The loss coefficient for configuration 3 was 0.177, compared with a value of 0.224 for the unslotted stator.

Loss coefficient and D-factor values for the four stator configurations are given in table V-5.

Table V-5. Data Summary for Annular Cascade Stator Test Configurations

CONFIGURATION	SLOT GEOMETRY	$\bar{\omega}_{2-3A}$	D-FACTOR	LIFT COEFFICIENT	TURNING, deg
1	Unslotted	0.224	0.482	0.795	37.3
2	Small r_1; Thin Slot	0.220	0.528	0.838	39.4
3	Large r1; Thick Slot	0.177	0.526	0.945	38.8
4	Large r_1; Thin Slot	0.191	0.514	0.955	39.3

The D-factor loading values in table V-5 indicate a significant increase in loading for the slotted tests. The higher D-factor values at midspan for the slotted vane configurations occurred because the static pressure rise values were higher than for the unslotted configuration. Although no measurements were made near the walls, the implication is that losses there were reduced giving less blockage and less axial velocity increase at midspan. Slotted stator configuration 3 has approximately a 10% higher D-factor and 20% lower loss coefficient than the unslotted stators.

Pressure coefficient distributions for the slotted stator configurations are presented in figure V-6. The unslotted stator pressure coefficient distribution is included in the figure for comparison. Different symbols are used to differentiate pressure measurements obtained with vanes A, B, and C. Pressure coefficient data values for the slotted stator configurations are presented in table V-2 in Appendix B. The suction surface diffusion appears to have been improved by addition of the slot. A second minimum pressure point occurs on the Coanda radius at the downstream side of the slot. This minimum pressure is caused by the acceleration of slot flow over the Coanda radius, and is considered to be a prime factor in the mechanism of slot effectiveness.

Lift coefficients were calculated by manually integrating the pressure coefficient distributions. Lift coefficients for each configuration are listed in table V-5. All of the slotted stator configurations show an improvement over the unslotted stator; configurations 3 and 4 show the most significant gain in lift coefficient.

Slotted stator exit air angle measurements are summarized in table V-4 (page V-2). The average exit air angle was obtained from two of the three probes that were located in the test section (behind slotted stators) at 24.4 and 65.8 degrees. The angle measurements obtained with the probe located at 228.5 degrees were not used because this probe was not in the test section. The angle measurements obtained at 328.8 degrees were omitted from the average because the indicated air angles for two of the four configurations are considerably different from those indicated for the other two configurations for no apparent reason. The average air angle is 7.9 degrees. This gave an average turning angle of 41.3 degrees for all of the slotted configurations, which is not significantly different from the average turning for the unslotted stator. The midspan values of turning do not reflect the increase in lift coefficient obtained by adding slots to the stators. This apparent discrepancy is attributed to three-dimensional flow effects that were not accounted for in the data measurements.

B. GUIDE VANE EVALUATION

1. Cruise Geometry

The total pressure wake profile for the cruise geometry guide vanes is shown in figure V-7. Kiel and wedge probe readings were translated to the wake probe channel and are superimposed on the wake profile for comparison. The guide vane total pressure loss coefficient for this configuration is 0.0167.

The guide vane exit air angle was 28.1 degrees and 25.3 degrees for the traverse probes located at circumferential locations 6.5 and 319.5 degrees, respectively. This gave an average air turning of 26.7 degrees which is 3.3 degrees less than the design value of 30 degrees.

The cruise geometry configuration portion of the inlet guide vane program was originally intended to include evaluation of a slot in the rear flap section of the guide vane. The initial unslotted configuration was tested without a slot to provide a baseline for evaluation purposes. Analysis of the initial test data indicates that the inlet guide vane had achieved almost design turning, with a relatively low profile loss. It was therefore decided that a slot in the flap would not further improve vane turning, and the slot portion of this program was not conducted. The rear flap section of the variable geometry guide vane for the rotating cascade program will be slotted, however, to aid turning at flap angles greater than those for design turning (30 degrees).

2. Design (Axial Flow) Geometry

The purpose of the second part of the inlet guide vane program was to compare the total pressure losses of the two candidate variable geometry concepts when they are configured for axial exit flow. Total pressure wake profiles for the two variable geometry designs are shown in figure V-8. The wake of the venetian blind variable geometry concept is seen in the figure to be larger than the wake for the variable camber design. The corresponding loss coefficients are 0.021 for the variable camber and 0.069 for the venetian blind.

SECTION VI
CONCLUDING DISCUSSION

A preliminary annular cascade program was conducted for the evaluation of stator slot design and two candidate guide vane designs as part of the design effort under an overall program to investigate variable geometry guide vane and stator concepts. The purpose of the slotted stator tests was to establish the feasibility of using a slot located near the leading edge to aid turning at off-design (high positive) incidence angles and to provide a design guideline for slot geometry. The guide vane evaluation was primarily concerned with the comparison of profile losses obtained with two variable geometry guide vane designs in the axial flow position. Because these evaluations were preliminary in nature, only mean radius air angle and total pressure data were obtained, and no attempts were made to refine the flow conditions and thereby the data.

The results of the evaluation of stator leading edge slots indicated that a slot at 22.5% chordal location produced a slight improvement in suction surface diffusion with an attendant increase in lift coefficient and decrease in loss coefficient when compared with the corresponding values obtained with an unslotted stator. Although three-dimensional flow effects may have influenced the absolute levels of these values, it is concluded that the slot geometry for slotted stator configuration 3 was superior to the other two slot geometries tested.

The evaluation of the two candidate guide vane designs indicated that the variable camber design gave significantly lower profile loss in the axial flow position. The high camber blade for the cruise geometry exhibited relatively low profile loss.

APPENDIX A
LIST OF SYMBOLS

Symbol	Description	Units
c	Chord length	in.
C_L	Lift coefficient	
C_p	Static pressure coefficient	
M	Mach number	
p	Static pressure	psia
P	Total pressure	psia
q	Dynamic pressure, $1/2\rho V^2$	psia
s	Blade spacing	in.
V	Velocity	ft/sec
β	Air angle, measured from axial line	deg
γ	Ratio of specific heats	
γ°	Blade chord angle	deg
σ	Solidity	c/s
$\bar{\omega}$	Total pressure loss coefficient	

Subscripts

ℓ	Local vane surface point	
p	Pressure surface	
s	Suction surface	
θ	Tangential	
0	Prewhirl blade inlet station (stator tests) Guide vane exit station (guide vane tests)	
1	Prewhirl blade exit station	
2	Stator inlet station	
3A	Stator exit station	

APPENDIX B
TABULATED DATA

The following data tabulations are included:

Table IV-1	Wall Static Pressure, Weight Flow, and Mach Number For Stators
Table V-1	Midspan Stator Inlet Air Angles
Table V-2	Static Pressure Coefficients for Stators
Table V-3	Stator Program - Total Pressure (psia) - Midspan at Station 3A (Stator Exit)

Table IV-1. Wall Static Pressure, Weight Flow, and Mach Number For Stators

	UNSLOTTED	SLOTTED		
Configuration	1	2	3	4
Plenum Pressure	14.392	14.681	14.593	14.561
Tap Circumferential Position:		Station 2 (Stator Inlet)		
193.5° ID	12.014	12.272	12.226	12.339
83.0° ID	12.013	12.387	12.662	12.392
3.0° ID	11.535	11.680	11.405	11.412
263.0° OD	12.535	12.786	12.639	12.749
133.0° OD	12.372	12.738	12.564	12.616
32.5° OD	12.224	12.369	12.392	12.337
		Station 3A (Stator Exit)		
331.5° OD	12.383	12.572	12.720	12.760
295.5° OD	12.556	14.911*	14.812*	14.790*
238.8° OD	12.384	12.669	12.631	12.655
169.5° OD	12.460	12.812	12.716	12.786
115.5° OD	12.532	12.897	12.801	12.781
61.5° OD	12.362	12.834	12.888	12.731
43.5° OD	12.570	14.913*	12.950	12.848
7.5° OD	12.626	13.075	12.987	12.884
193.9° ID	12.559	12.943	12.947	12.927
48.7° ID	12.529	12.924	12.958	12.796
$\dot{\omega}$, lb/sec	70.52	70.11	69.99	70.73
M_2	0.495	0.493	0.492	0.489

Pressure units are psia

*Not used to obtain average values

Table V-1. Midspan Stator Inlet Air Angles

	STATION 1		STATION 2	
Circumferential Location (deg)	18	63	143	323
Configuration 1 (unslotted)	50.1	47.4	47.0	45.5
Configuration 2	50.4	46.8	48.3	--
Configuration 3	48.9	46.2	49.1	47.6
Configuration 4	47.4	44.8	46.8	48.5

Table V-2. Static Pressure Coefficients for Stators

SUCTION SURFACE

TAP NO.	Unslotted Stator	Slotted Stators		
	Configuration 1	Configuration 2	Configuration 3	Configuration 4
1	-1.0839	-1.2990	-1.8803	-1.5981
2	-0.7554	-0.8346	-1.2125	-1.0125
3		0.1389	-0.1707	-0.7629
4	-0.4218	0.9327	0.1442	1.0058
5	-0.2877	1.1543	0.2246	1.0506
6	-0.1825	-0.5885	-0.6433	-1.3253
7	-0.1114	-0.4106	-0.4884	-0.6318
8	-0.0692	-0.3005	-0.3947	-0.4549
9	-0.0308	-0.1813	-0.2966	-0.3263
10	-0.0109	-0.1269	-0.2341	-0.2376
11	0.0133	-0.0913	-0.1726	-0.0742
12	0.0275	0.0168	-0.0894	-0.0173
13	0.0346	0.0899	-0.0221	0.0424
14	0.0459	0.0937	0.0211	0.0795
15	0.0351	0.1404	0.0341	0.1094
16	0.0536	0.1582	0.0639	0.1518
17	0.0474	0.1836	0.0832	0.1508
18	0.0569		0.1000	0.1692
19	0.0673	0.2110	0.1327	0.1677
20	-2.1483	-2.3481	-1.7736	-2.4636
21	-1.3019	-1.4841	-1.0798	-1.4173
22	-1.0701	-0.9678	-0.4548	-0.1595
23	-0.7332	-0.7629	0.7048	-0.7879
24	-0.5720	0.6274	-0.9490	0.6038
25	-0.4422	-0.9788	-0.6135	-1.1238
26	-0.3265	-0.6933	-0.3759	-0.8472
27	-0.2389	-0.5740	-0.2596	-0.6448
28	-0.1607	-0.4360	-0.1813	-0.5098
29	-0.1332	-0.3279	-0.0879	-0.3855
30	-0.1024	-0.1913	-0.0351	-0.3108

Table V-2. Static Pressure Coefficients for Stators (Continued)

TAP NO.	Unslotted Stator Configuration 1	Slotted Stators Configuration 2	Slotted Stators Configuration 3	Slotted Stators Configuration 4
SUCTION SURFACE				
31	-0.0692	-0.1288	0.0308	-0.1581
32	-0.0436	-0.0822	-0.0202	-0.1026
33	-0.0398	-0.0168	0.1096	-0.0395
34	-0.0322	0.0303	0.1514	-0.0202
35	-0.0265	0.0654	0.1750	0.0328
36	-0.0090	0.1014	0.2091	0.0689
37	-0.0251	0.1077	0.2067	0.0896
38	-0.0118	0.1245	0.2005	0.1176
PRESSURE SURFACE				
1	0.7834	0.6519	0.7788	0.6669
2	0.6644	0.6706	0.4476	0.6723
3	0.5919	0.8029	0.5389	0.8077
4	0.5303	0.5481	0.6101	0.5152
5	0.4967	0.5385	0.5793	0.5263
6	0.4564	0.5245	0.5471	0.4636
7	0.4450	0.4745	0.5168	0.4737
8	0.4218	0.4490	0.4784	0.4501
9	0.4184	0.4442	0.4726	0.4501
10	0.4237	0.4514	0.4736	0.4458
11	0.4294	0.4611	0.4774	0.4578
12	0.4384	0.4822	0.4937	0.4675
13	0.4554	0.5115	0.5255	0.5094
14	0.4881	0.5139	0.5308	0.5123
15	0.4943	0.5230	0.5351	0.5248
16	0.4934	0.5279	0.5428	0.5316
17	0.4948	0.5370	0.5433	0.5364
18	0.4938	0.5557	0.5313	0.5316
19	0.4161	0.4721	0.4904	0.4612

Table V-3. Stator Program - Total Pressure (psia) - Midspan at Station 3A (Stator Exit)

			UNSLOTTED STATOR	SLOTTED STATORS		
Probe Type	Circumferential Location (deg)	Tube No.	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Wake Probe 1	358.8	1	14.3857	14.6729	14.5818	14.5415
		2	14.3907	14.6525	14.5647	14.5376
		3	14.3226	14.6158	14.5567	14.5016
		4	14.3376	14.5989	14.5457	14.4636
		5	14.3246	14.6069	14.5237	14.4585
		6	14.3497	14.6201	14.4856	14.4656
		7	14.0305	14.3119	14.1817	14.0486
		8	13.0896	13.5990	13.4248	13.4127
		9	12.6927	13.2472	13.1678	13.2167
		10	12.4292	13.1399	12.9869	12.9838
		11	12.4516	13.0380	12.8608	12.8638
		12	12.4247	12.9911	12.8208	12.8136
		13	12.4326	12.9520	12.8548	12.8427
		14	12.4737	12.9670	12.8958	12.8578
		15	12.5927	13.0170	12.9711	12.9137
		16	13.6317	13.9698	13.9547	13.9116
Wake Probe 2	280.5	17	13.0157	13.1719	13.7608	13.5007
		18	13.0397	13.2309	14.0008	13.6356
		19	13.4336	13.3820	14.1327	13.8296
		20	13.6446	13.6405	14.5930	13.9886
		21	13.8297	13.8118	14.3378	14.1355
		22	14.0556	14.0010	14.3506	14.1936
		23	14.5419	14.2119	14.4277	14.3156
		24	14.6082	14.3549	14.4388	14.3586
		25	14.3066	14.4468	14.4258	14.3886
		26	14.3006	14.7928	14.7157	14.6805
		27	14.3006	14.5089	14.4767	14.4295
		28	14.2897	14.5189	14.4946	14.4755
		29	14.5686	14.5278	14.5167	14.5396
		30	14.3087	14.6289	14.5647	14.5575
		31	14.3676	14.6328	14.5688	14.5505
		32	14.4917	14.6569	14.5727	14.5546

Table V-3. Stator Program - Total Pressure (psia) - Midspan at Station 3A (Stator Exit) (Continued)

		UNSLOTTED STATOR	SLOTTED STATORS		
Probe Type	Circumferential Location (deg)	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Wedge Probes	24.4	14.2307	14.3678	14.4748	14.2245
	65.8	13.7517	14.5488	14.1935	14.5086
	228.5	13.2806	13.3080	13.4066	14.2741
	328.8	14.2986	14.6309	14.5375	14.1561
Kiel Probes	13.8	12.6137	13.6449	13.7647	13.6755
	121.3	12.8461	12.9090	13.2188	12.9176
	294.2	14.3494	14.3678	14.4868	14.2245
	310.5	14.3156	14.3888	14.5157	14.2635
Plenum Pressure, P_{oo}		14.392	14.681	14.593	14.561

APPENDIX C
ILLUSTRATIONS

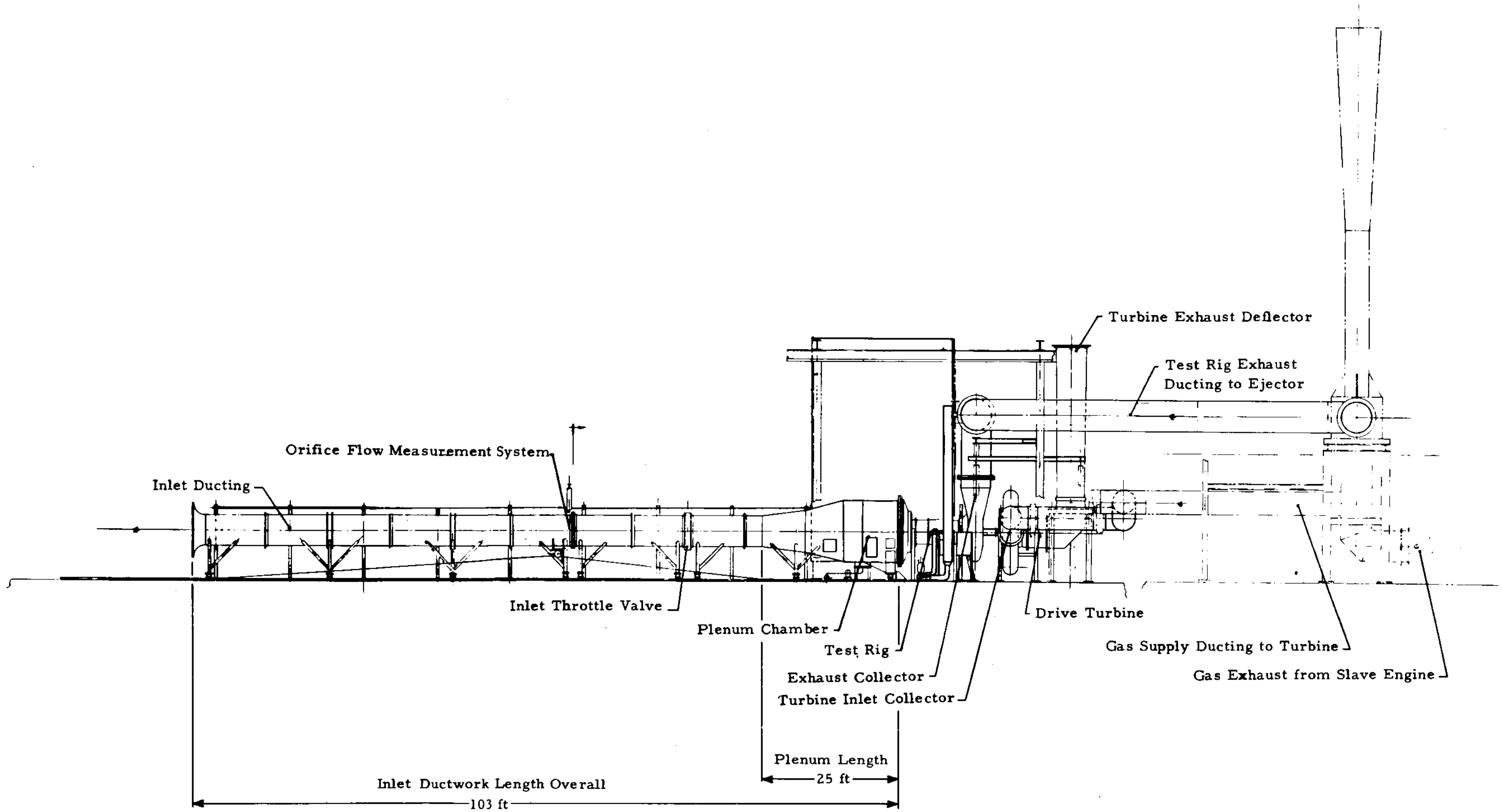
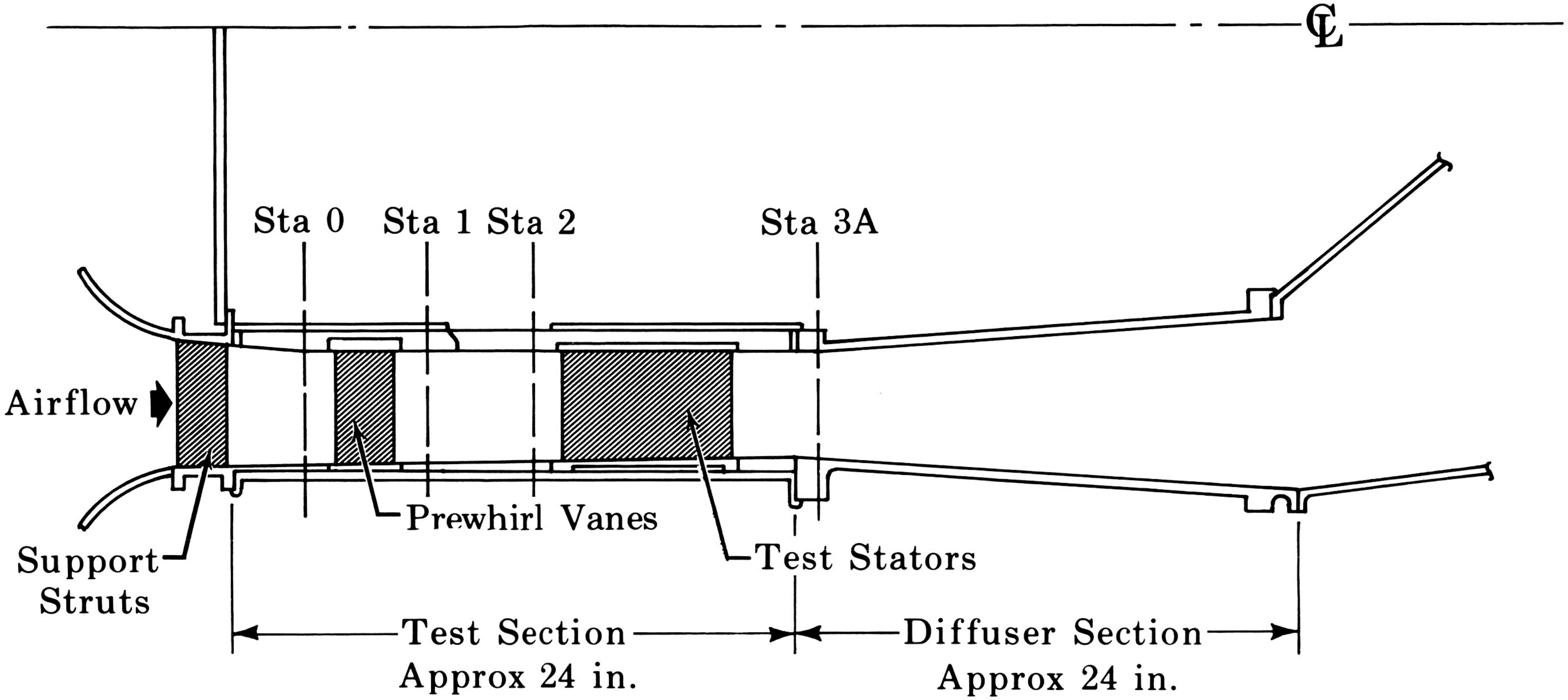


Figure III-1. Schematic View of Compressor Research Facility

FD 10891A



Measuring Station Diameters - in.

Station	ID	OD
0	32.38	41.12
1	32.85	40.57
2	32.85	40.23
3A	32.85	39.99

Figure III-2. Annular Cascade Test Rig Schematic - Stator Program

FD 14997C

FD 21937

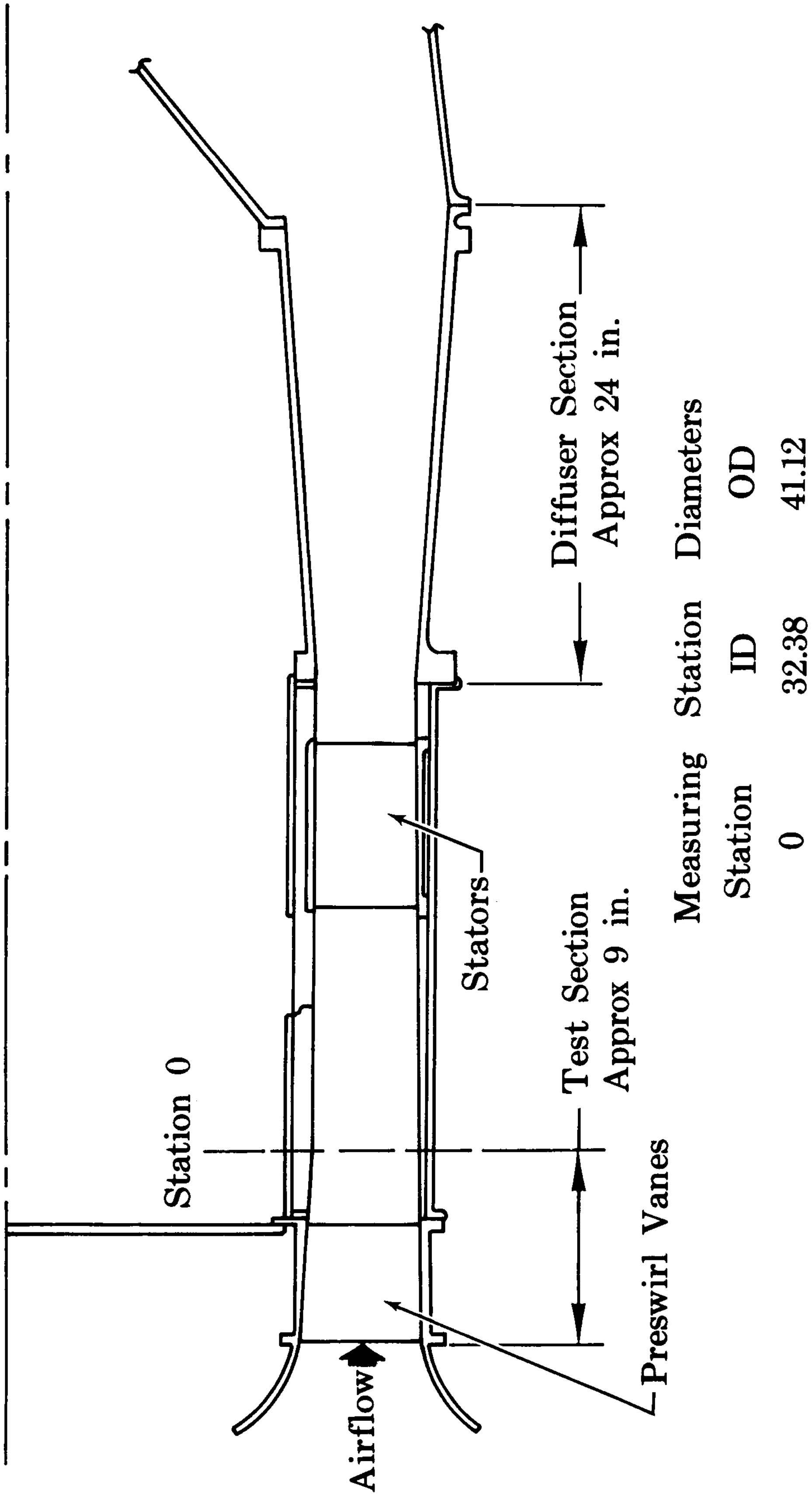


Figure III-3. Annular Cascade Test Rig Schematic - Guide Vane Program

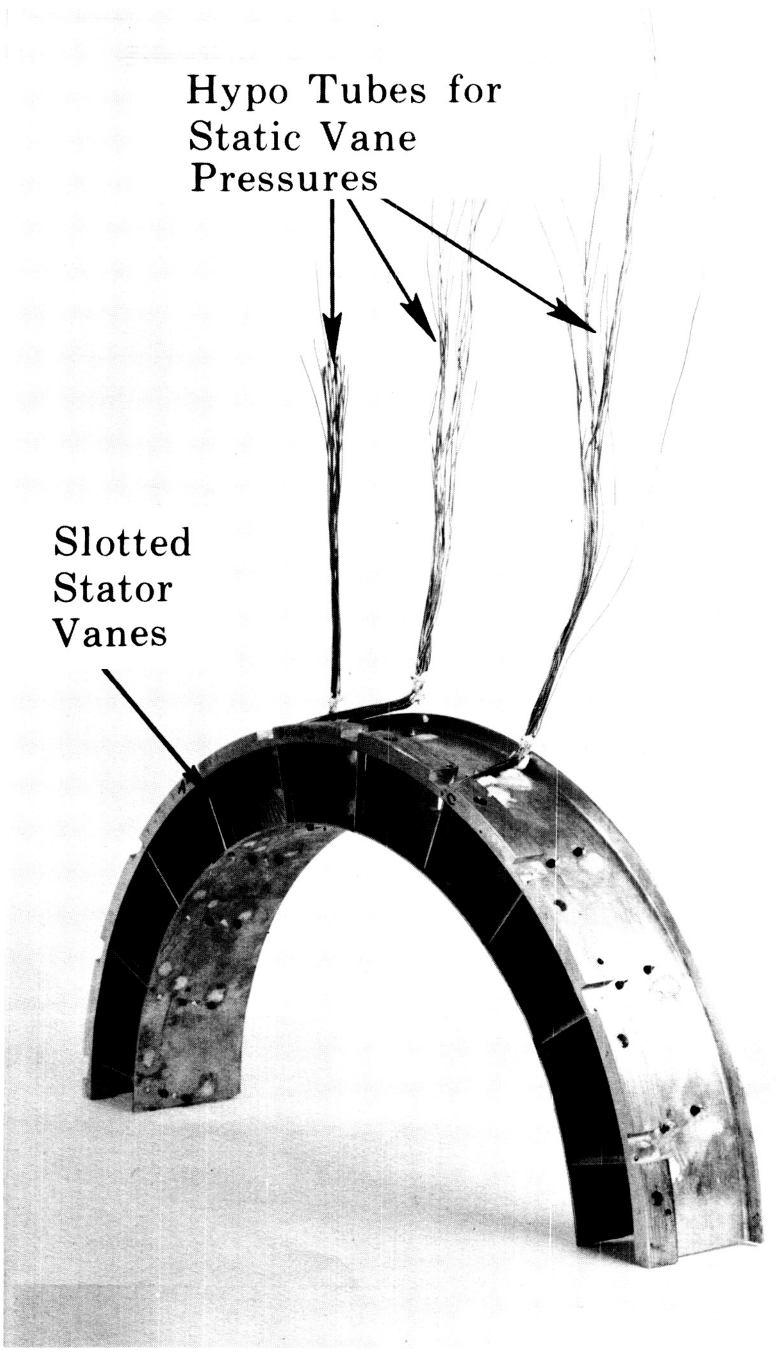


Figure III-4. Stator Vane Assembly FD 21941

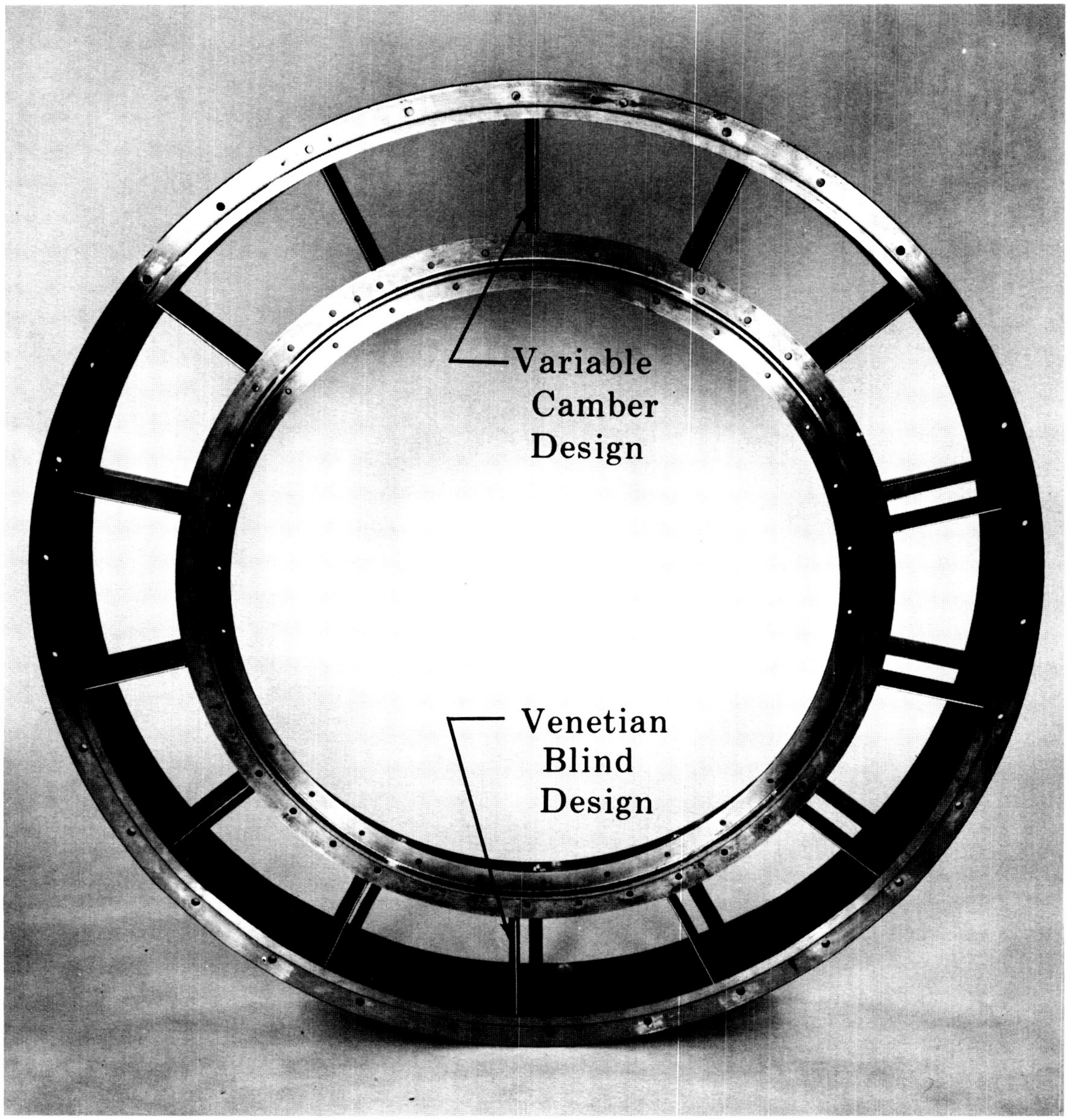


Figure III-5. Inlet Vane and Shroud Assembly for Design (Axial Flow) Inlet Guide Vane Test FD 21939

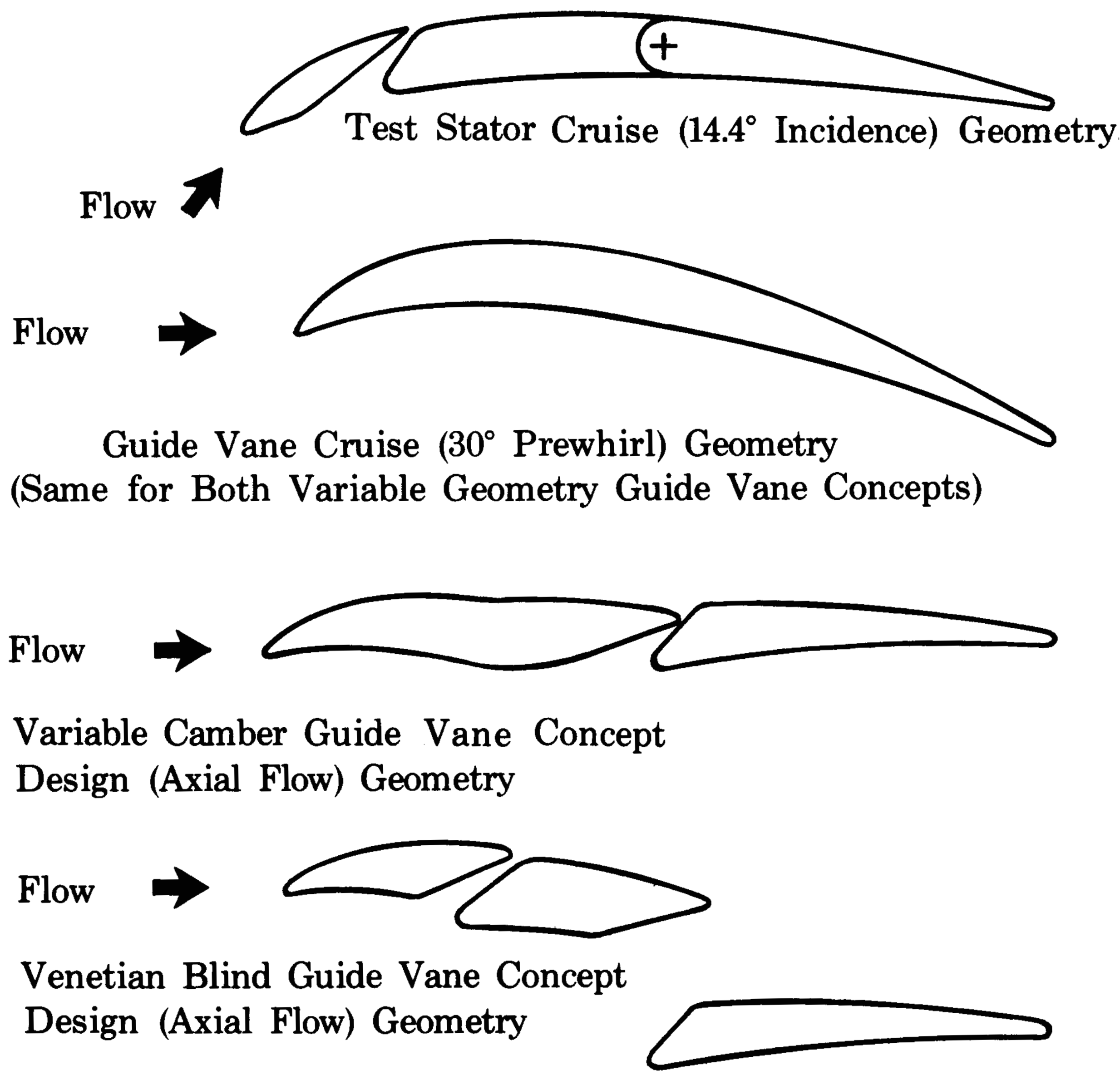
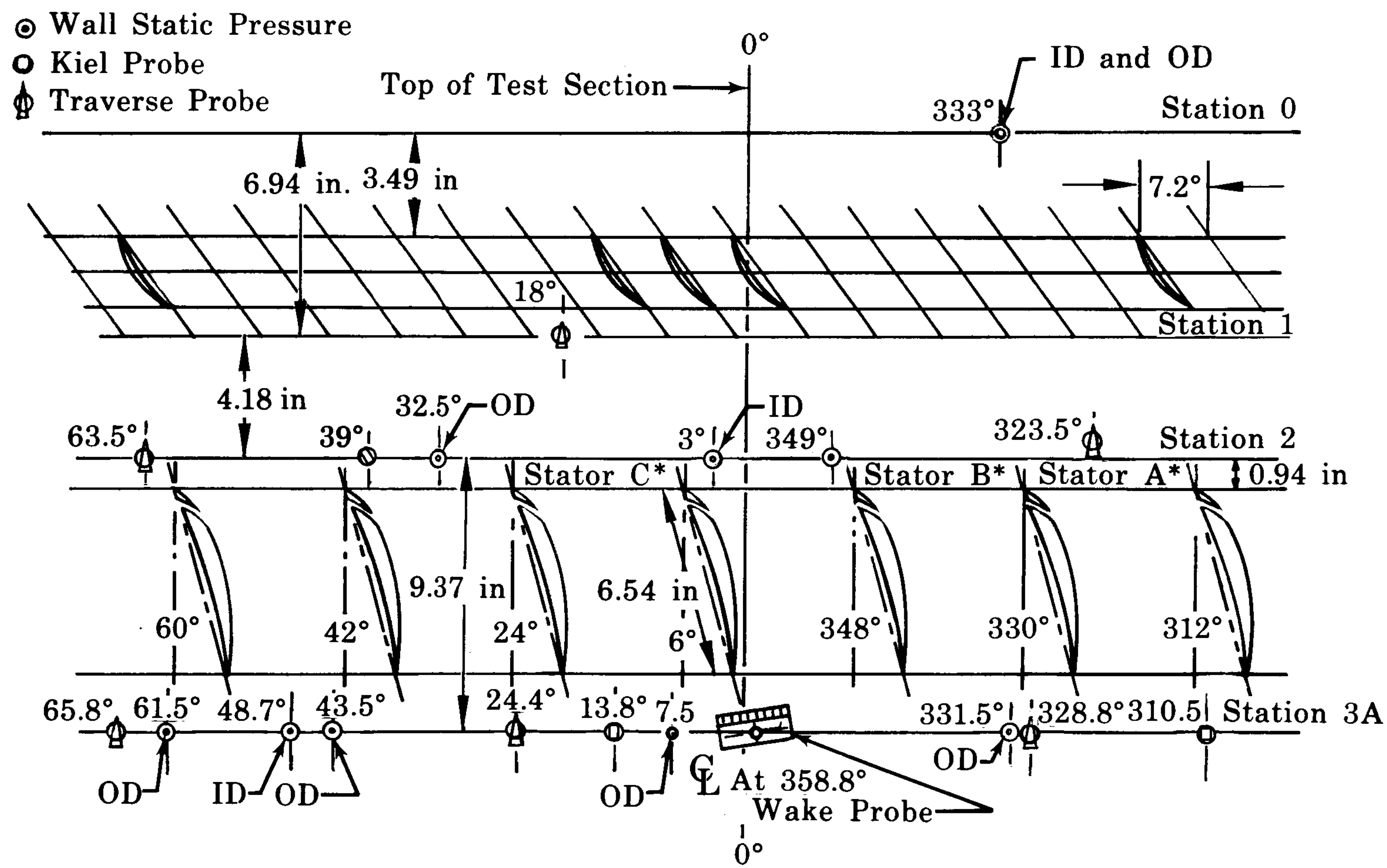


Figure III-6. Guide Vane and Stator Variable Geometry Concepts

FD 21940



Stator Vanes A,B, and C, Were Instrumented with Static Pressure Taps

Figure III-7. Test Section Instrumentation Layout, Stator Program

FD 21936

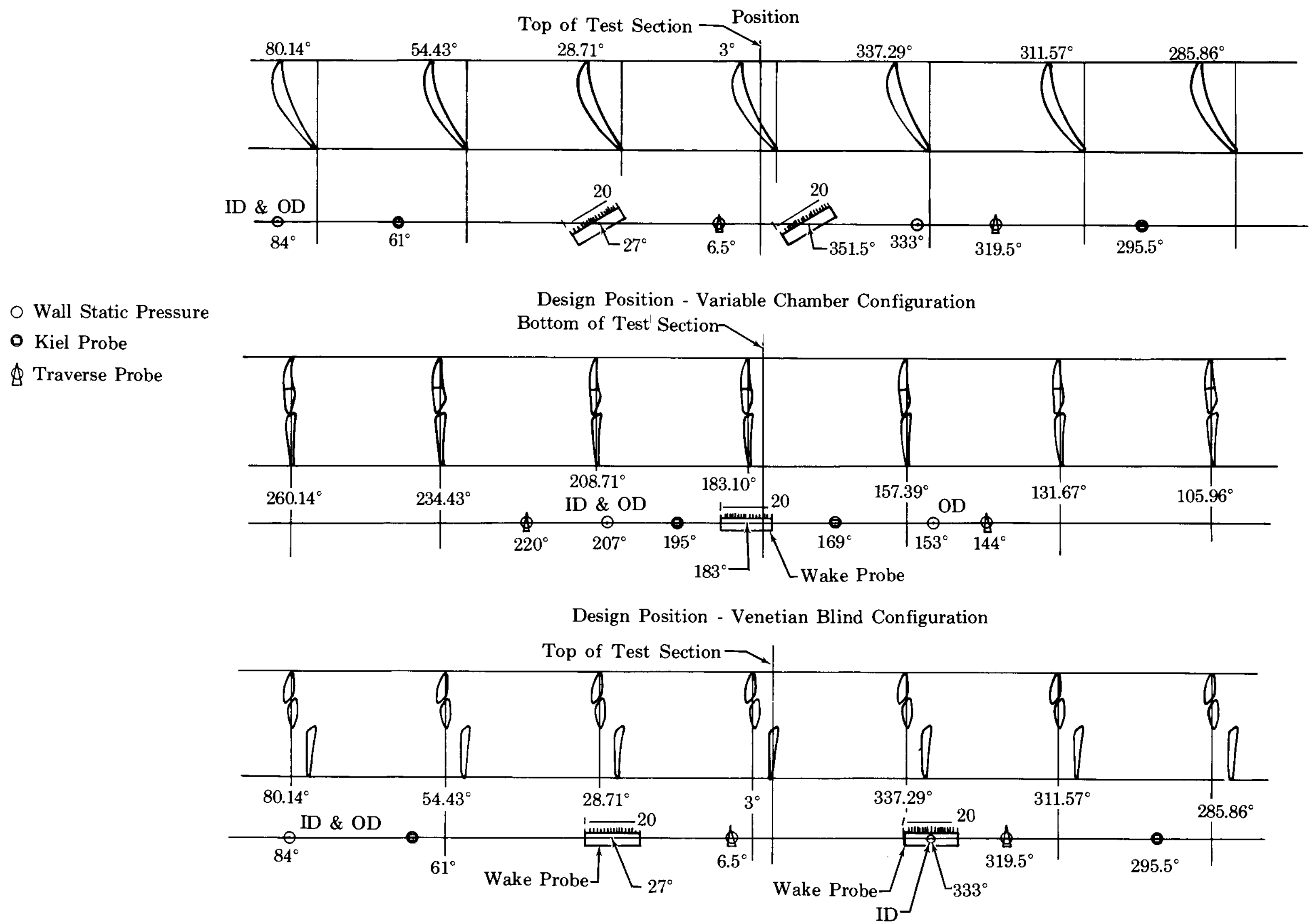


Figure III-8. Test Section Instrumentation Layout, Guide Vane Program (Cruise Position)

FD 21271

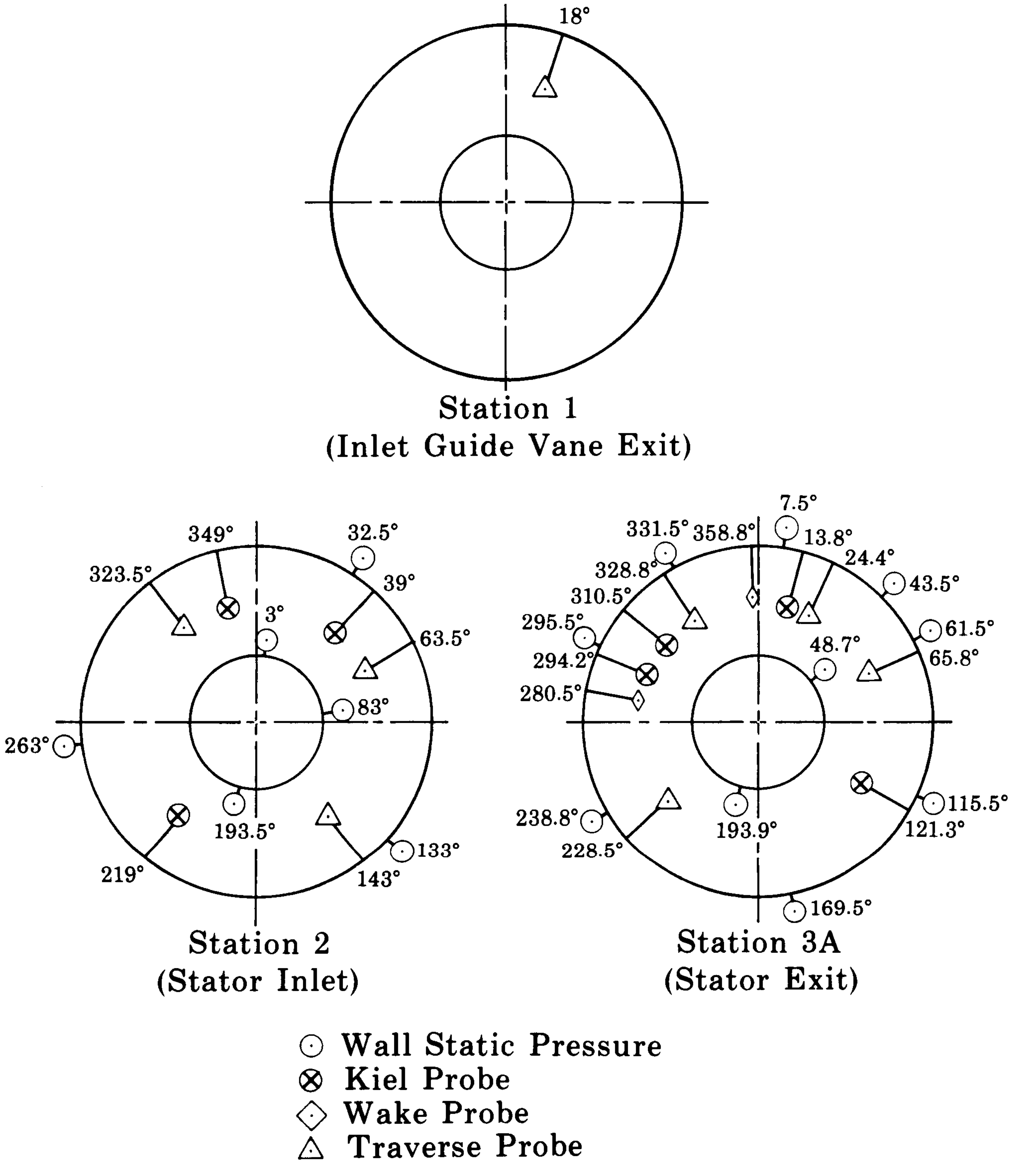


Figure III-9. Stator Program Instrumentation; Stations 1, 2, and 3A (View Looking Downstream) FD 14975B

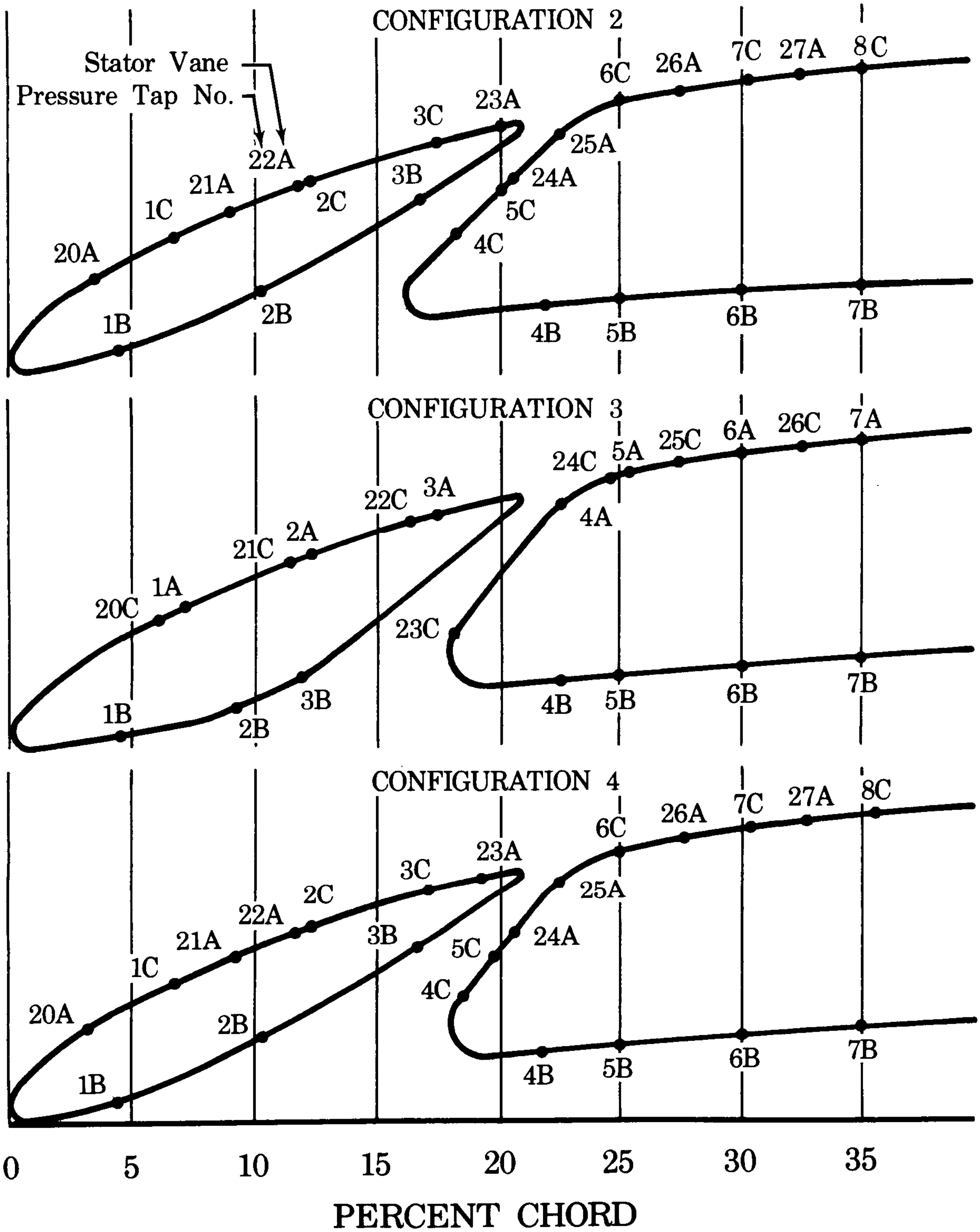


Figure III-10. Static Pressure Tap Locations Near Slot, Stator Program   FD 21938

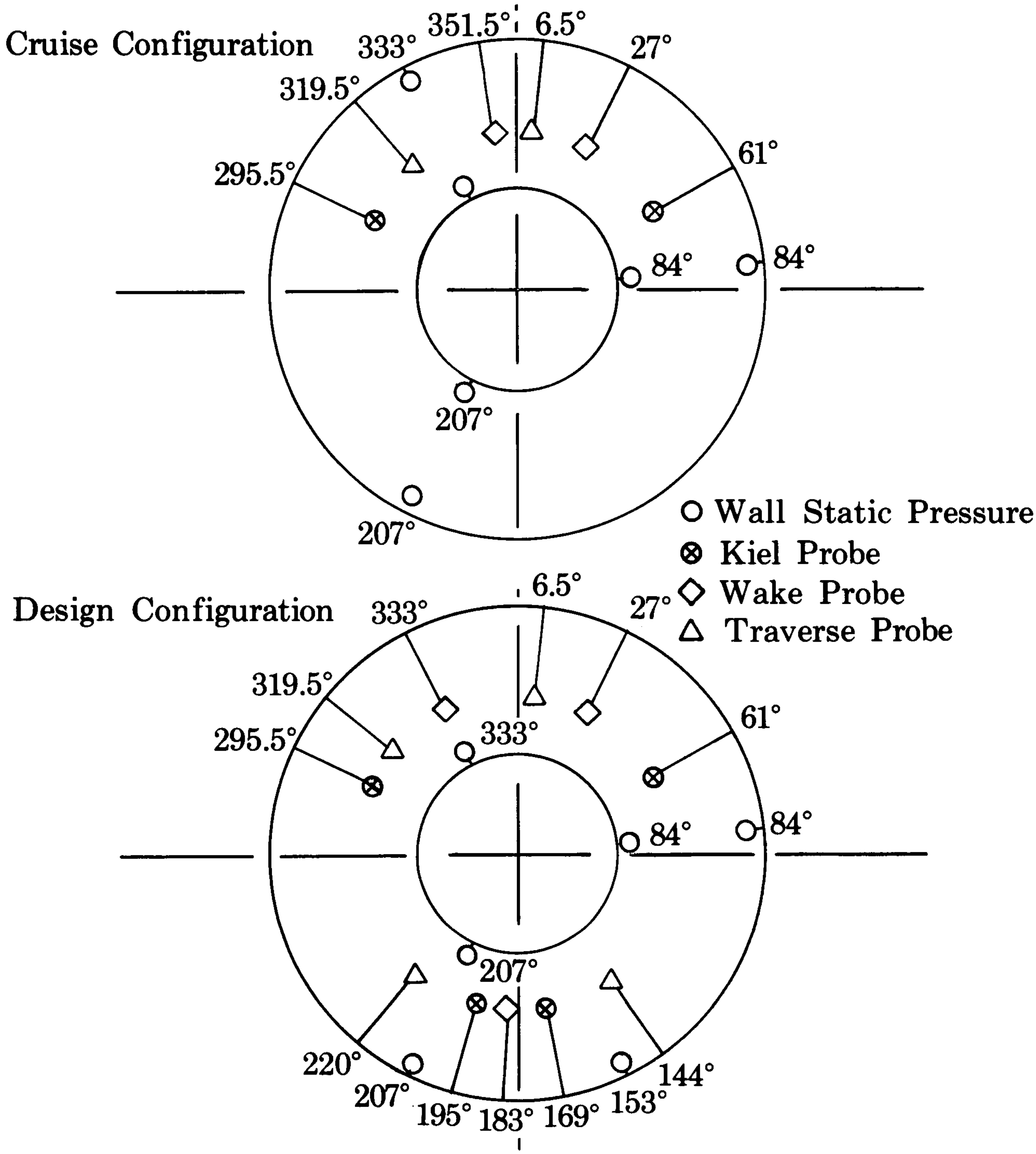


Figure III-11. Guide Vane Program Instrumentation at Station 0, Inlet Guide Vane Exit (View Looking Downstream) FD 21942

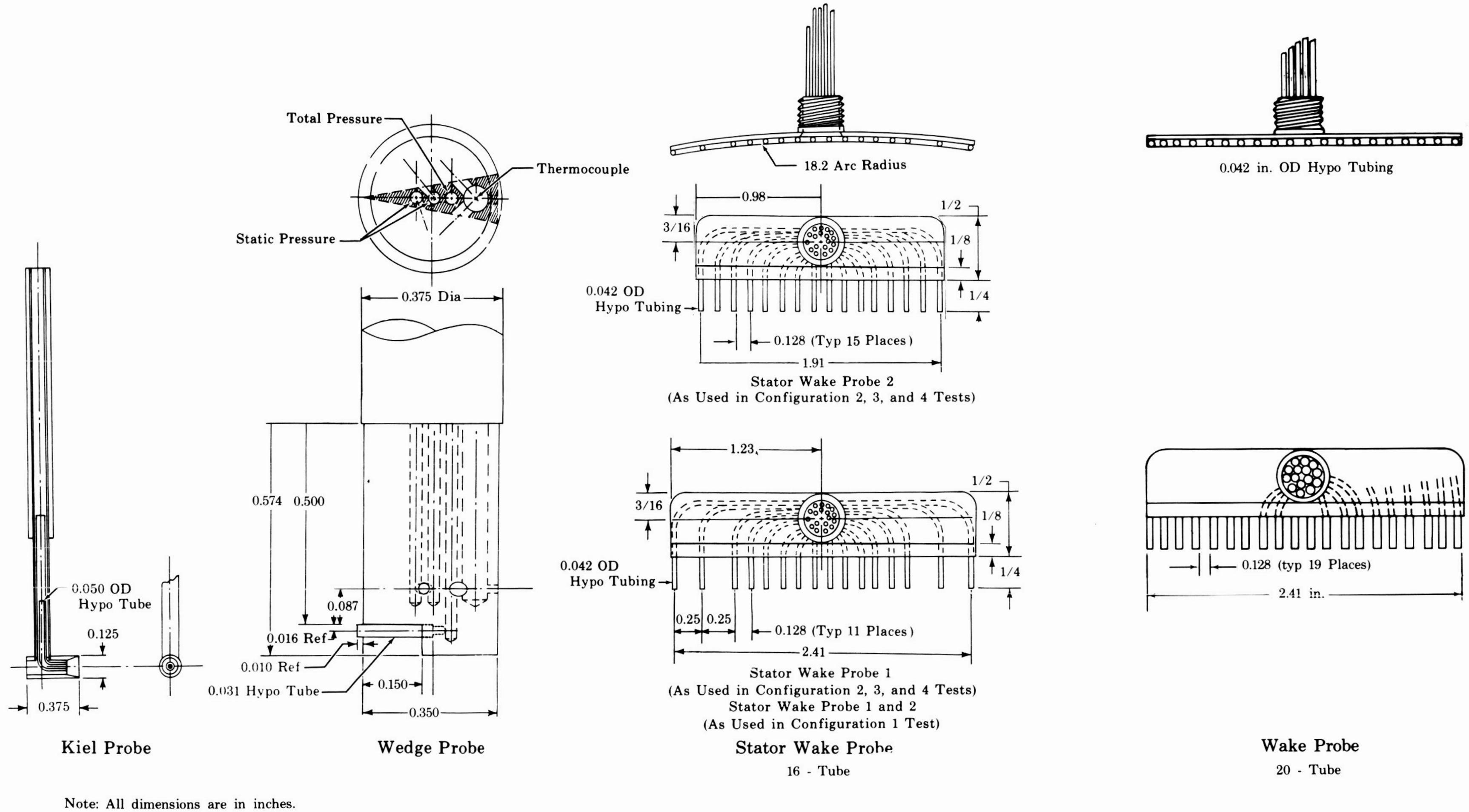


Figure III-12. Wedge and Kiel Total Pressure Probes

FD 21624

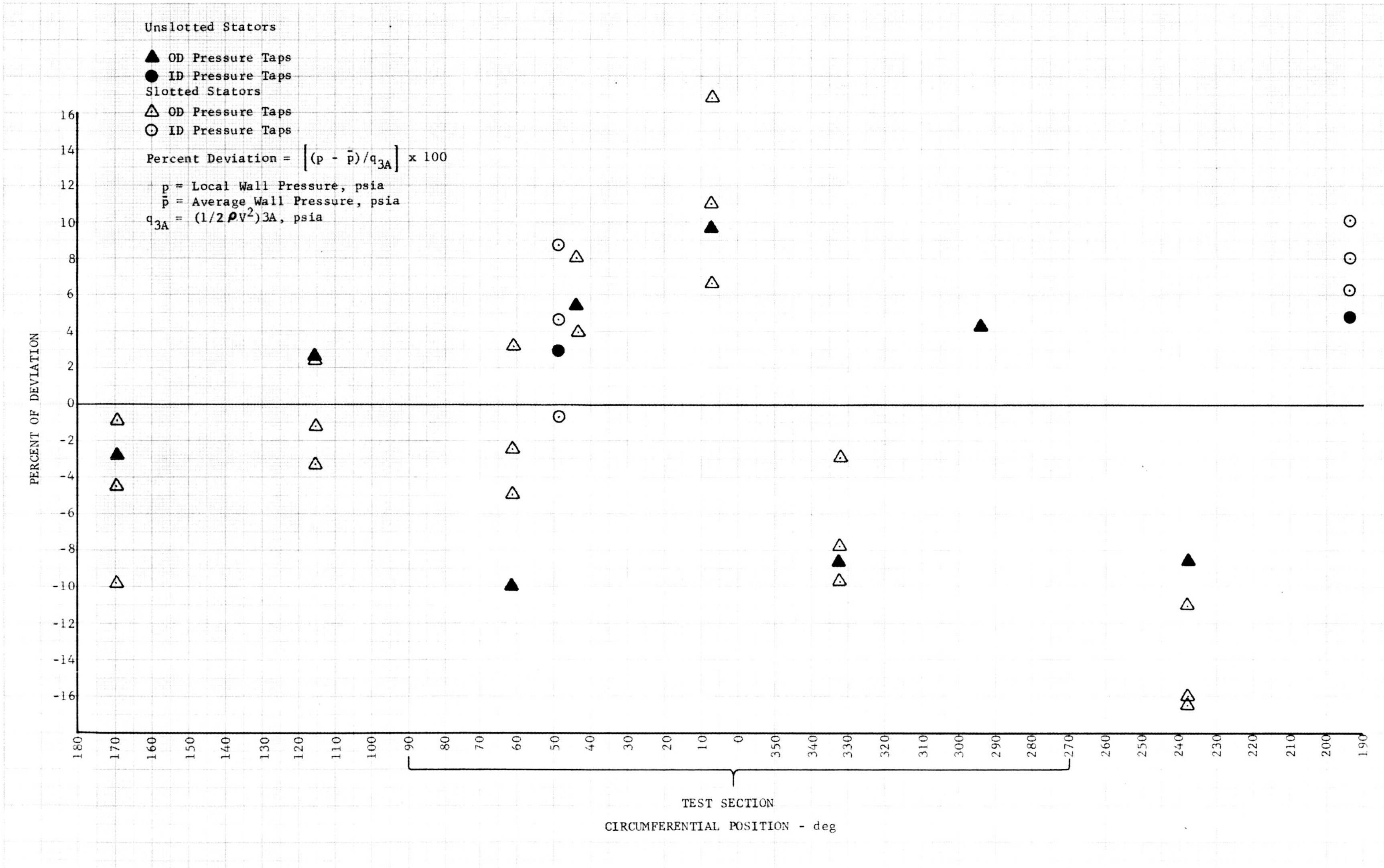


Figure IV-1. Circumferential Static Pressure Deviation at Stator Exit (Station 3A) for the Unslotted and Slotted Configurations

DF 55508

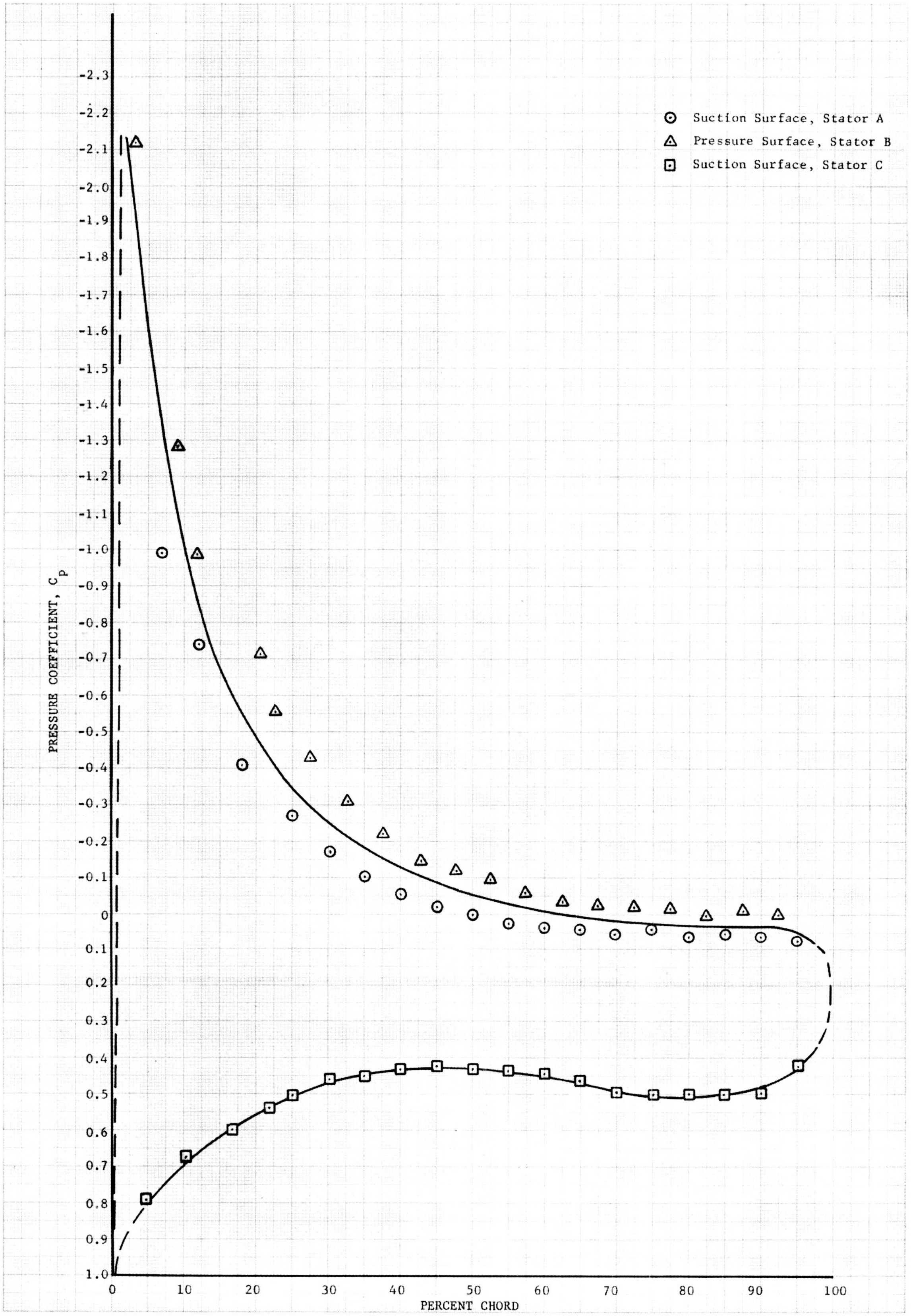


Figure V-1. Variation of Static Pressure Coefficient for Unslotted Stator Vane

DF 54845

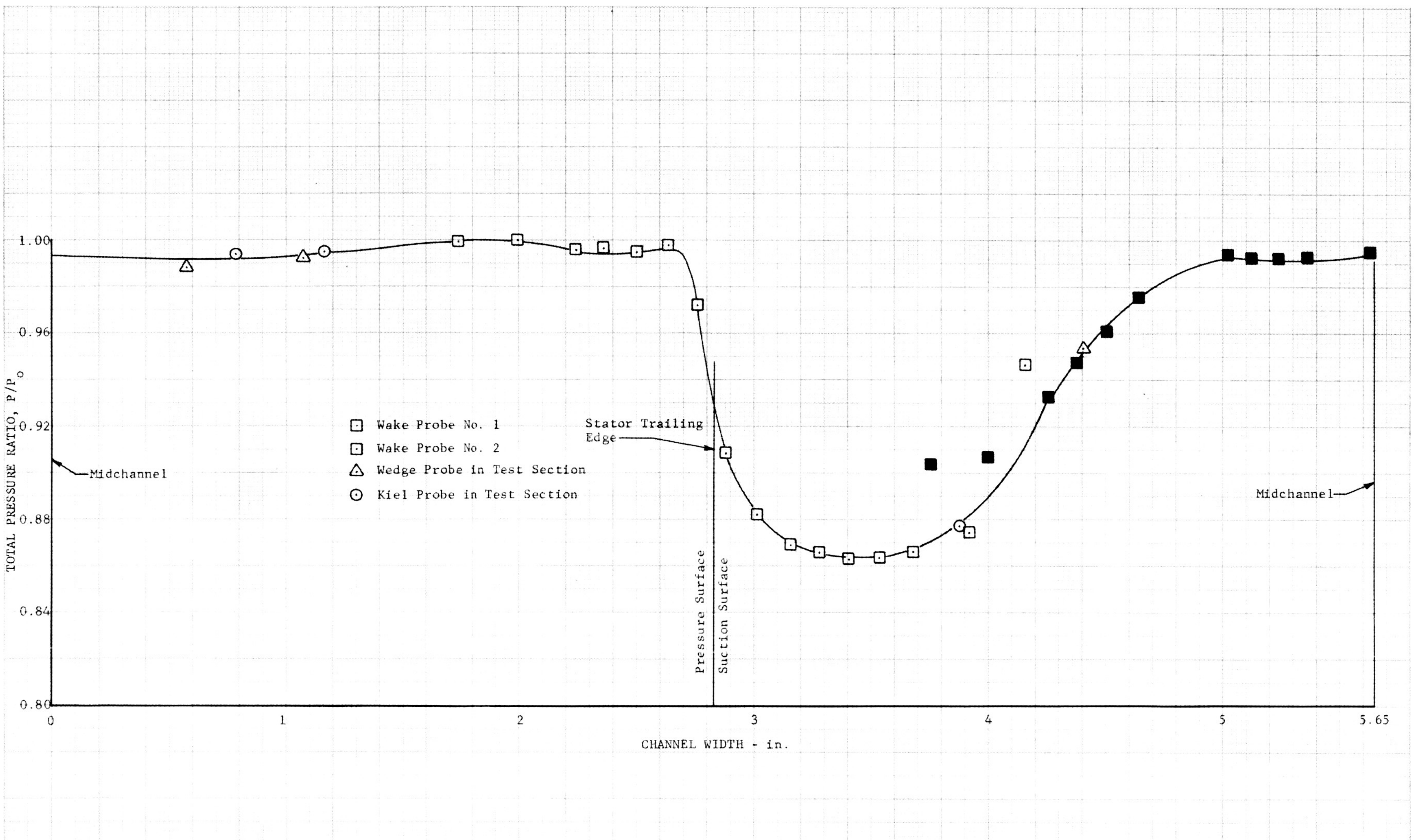


Figure V-2. Unslotted Stator Configuration 1 Wake Total Pressure Profile

DF 54846

R - Coanda Radius
r_1 - Slot Leading Edge Radius
r_2 - Slot Trailing Edge Radius
Y_1 - Slot Capture Dimension
Y_2 - Slot Exit Dimension
ψ_2 Angle Formed by Centerline and Mean Camber Line
R_p - Slot Pressure Surface Radius

Configuration	Y_2/Y_1	R	r_1	r_2	Y_1	Y_2
1	----------------	Unslotted	Vanes	----------------		
2	0.428	0.345	0.065	0.015	0.168	0.072
3	0.461	0.567	0.094	0.015	0.156	0.072
4	0.387	0.567	0.094	0.015	0.186	0.072

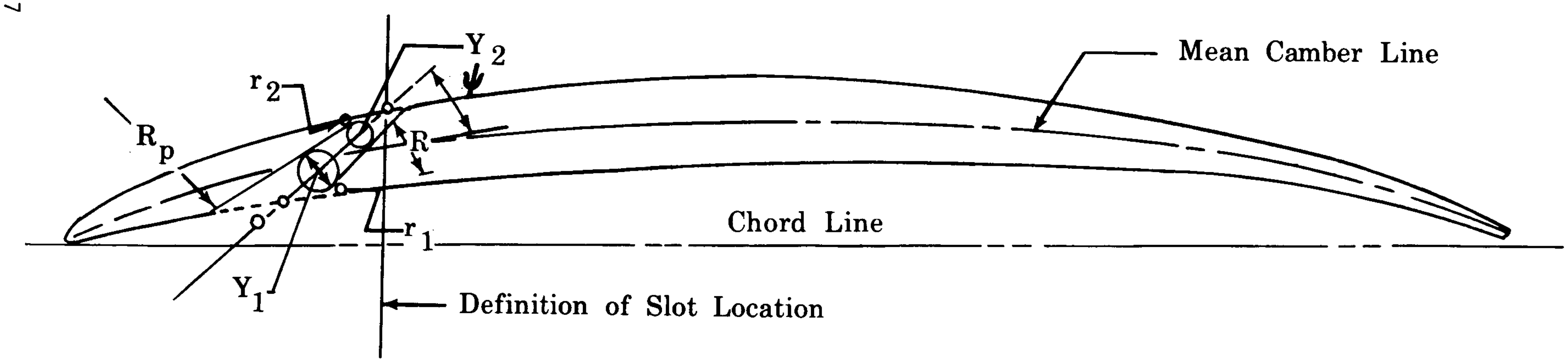
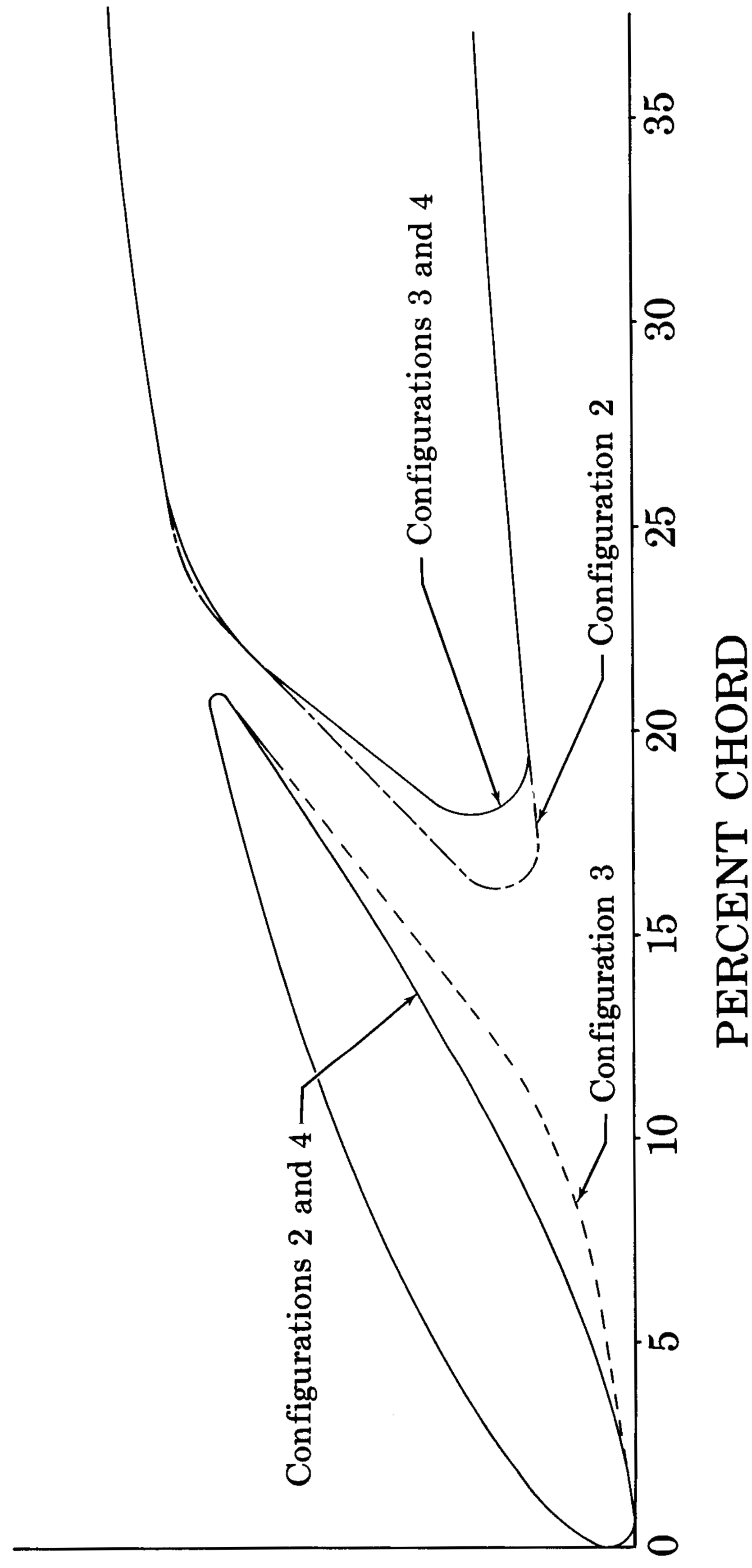


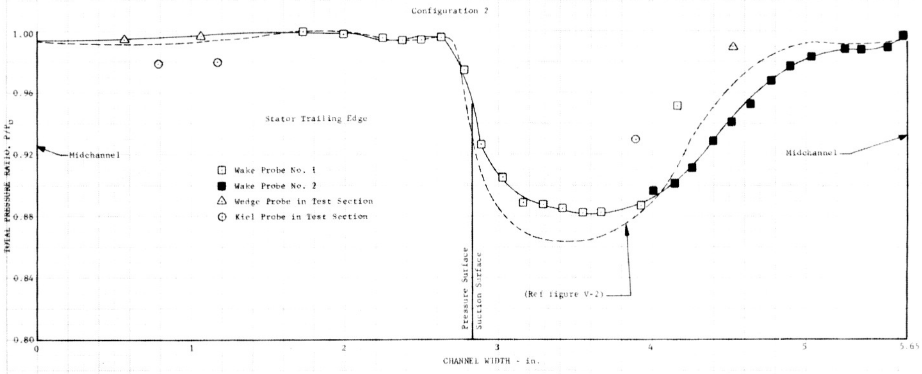
Figure V-3. Slot Geometry Nomenclature and Parameters

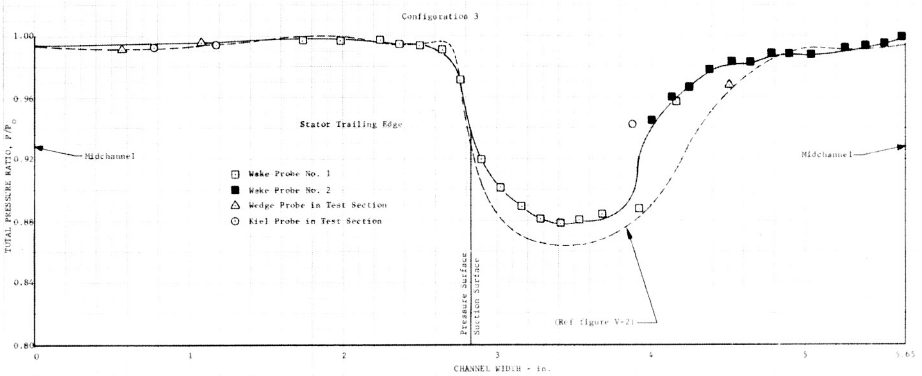
FD 21943



FD 19475

Figure V-4. Slot Configurations





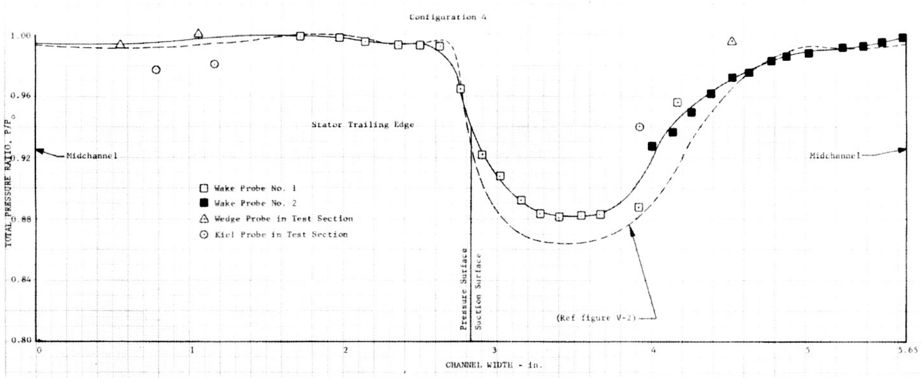


Figure V-5. Slotted Stator Wake Total Pressure Profile DF 54847-1,-2,-3

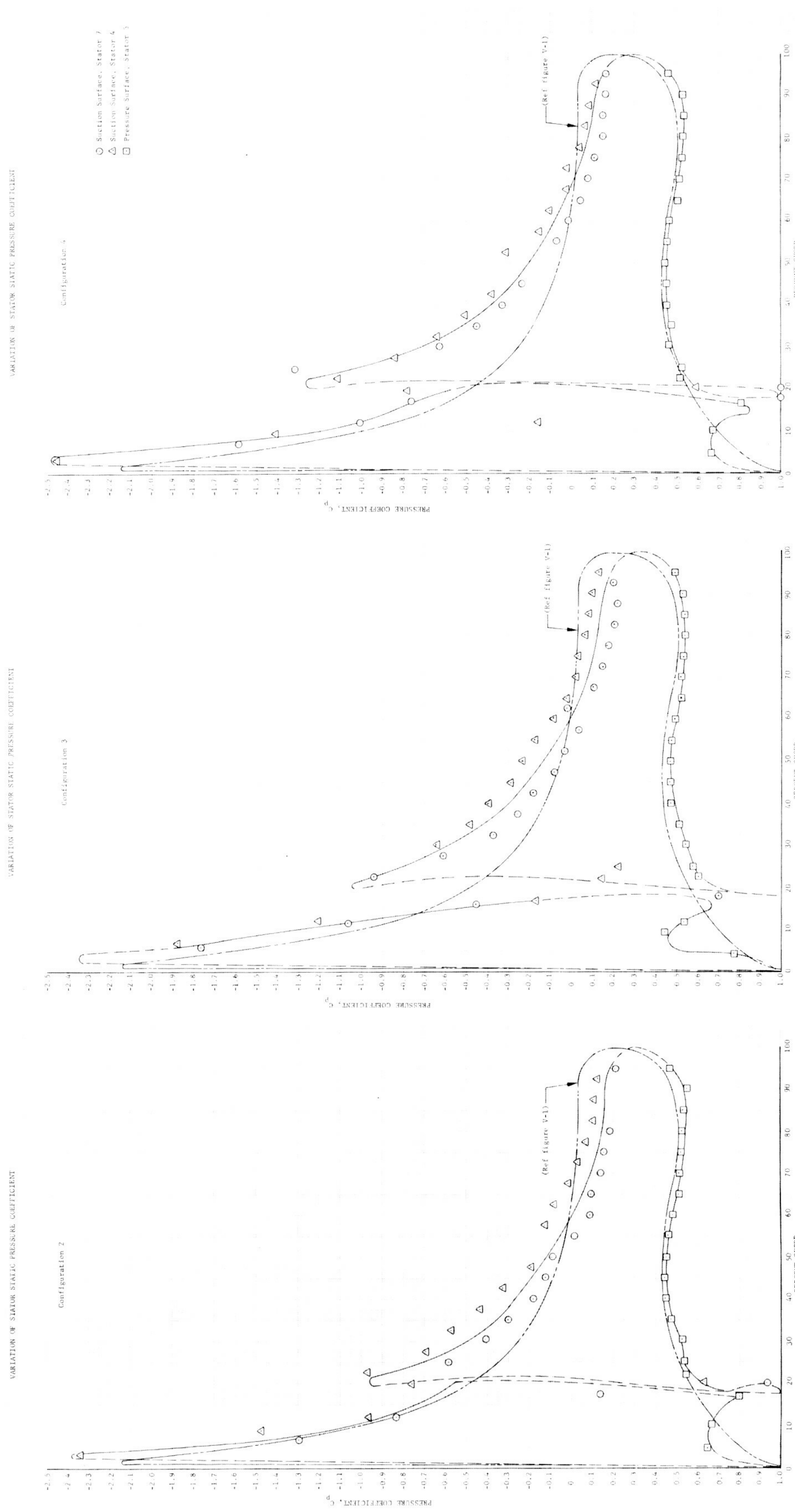
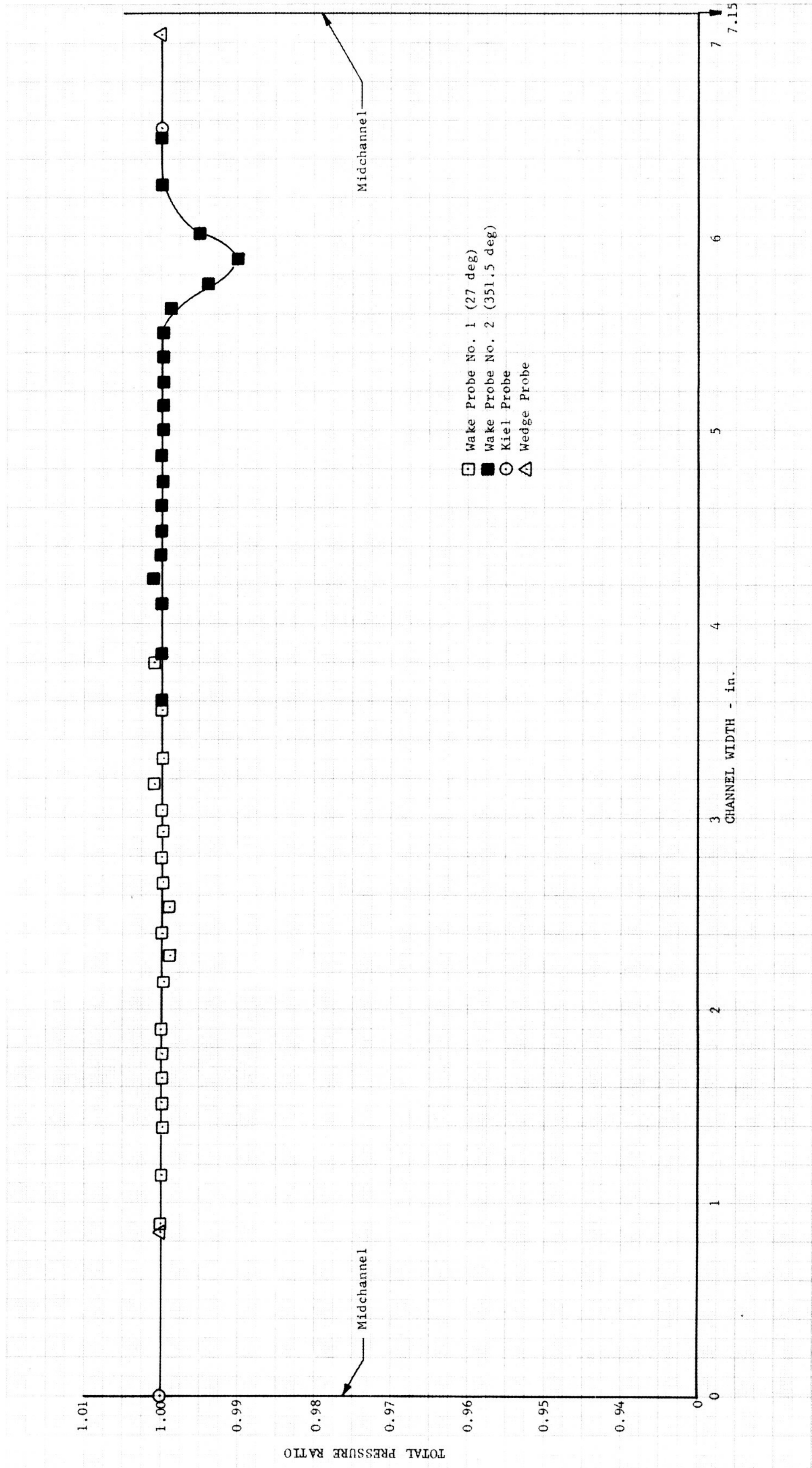


Figure V-6. Variation of Stator Static Pressure Coefficient

DF 54848-1,-2,-3



DF 54849

Figure V-7. Inlet Guide Vane Wake Total Pressure Profile - Axial Flow Position

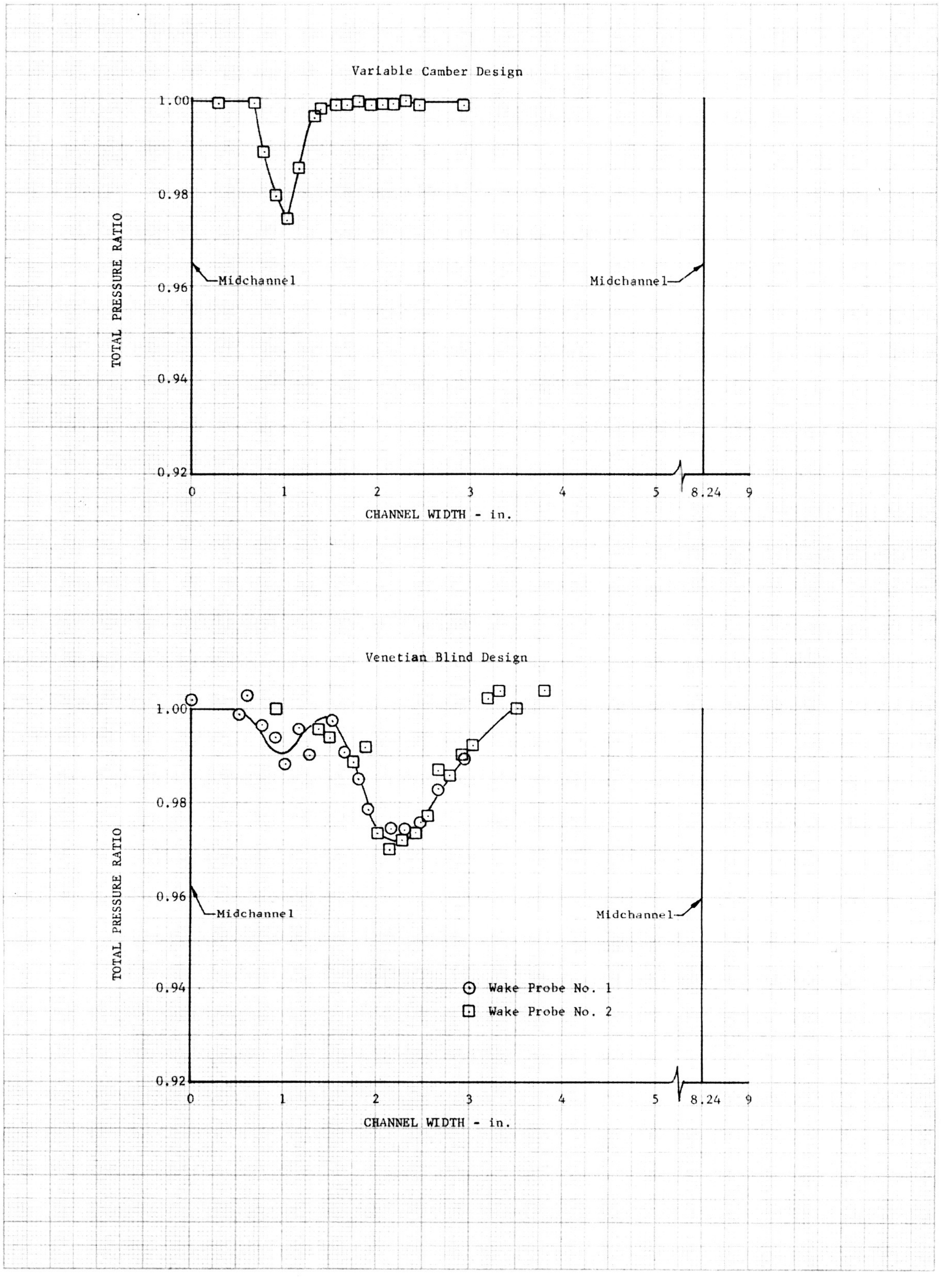


Figure V-8. Guide Vane Wake Total Pressure Profile

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APPENDIX D
REFERENCES

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